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Title: High-energy Particle Physics -- In Space!

Author(s): Albert, Andrea

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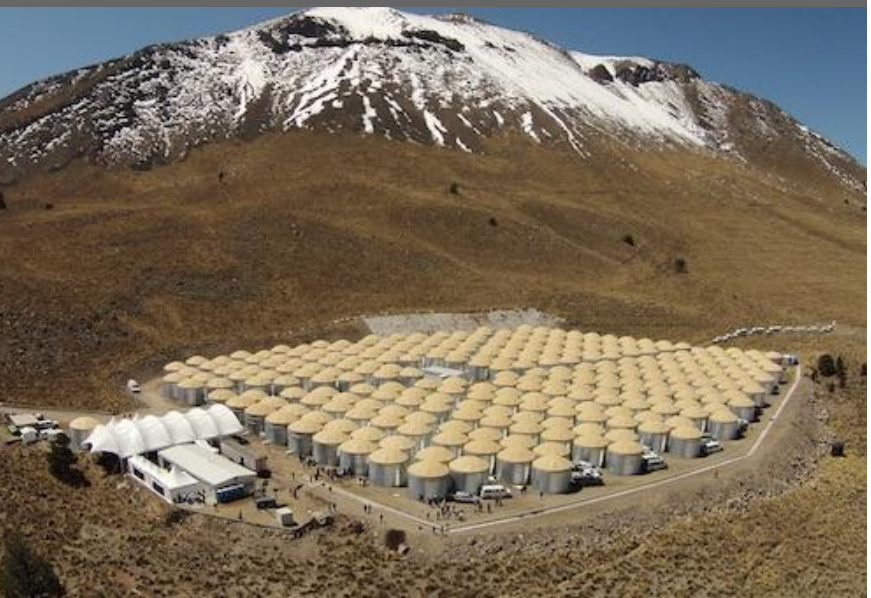
Fermi LAT & HAWC Collaborations



High-energy Particle Physics In Space!

Andrea Albert
Los Alamos National Laboratory

NEN Seminar
September 6, 2018

Photons are an Astronomical Probe

Quiver Tree Forest
Namibia Africa
http://apod.nasa.gov/apod/ap121212.html

Photons as an Astronomical Probe

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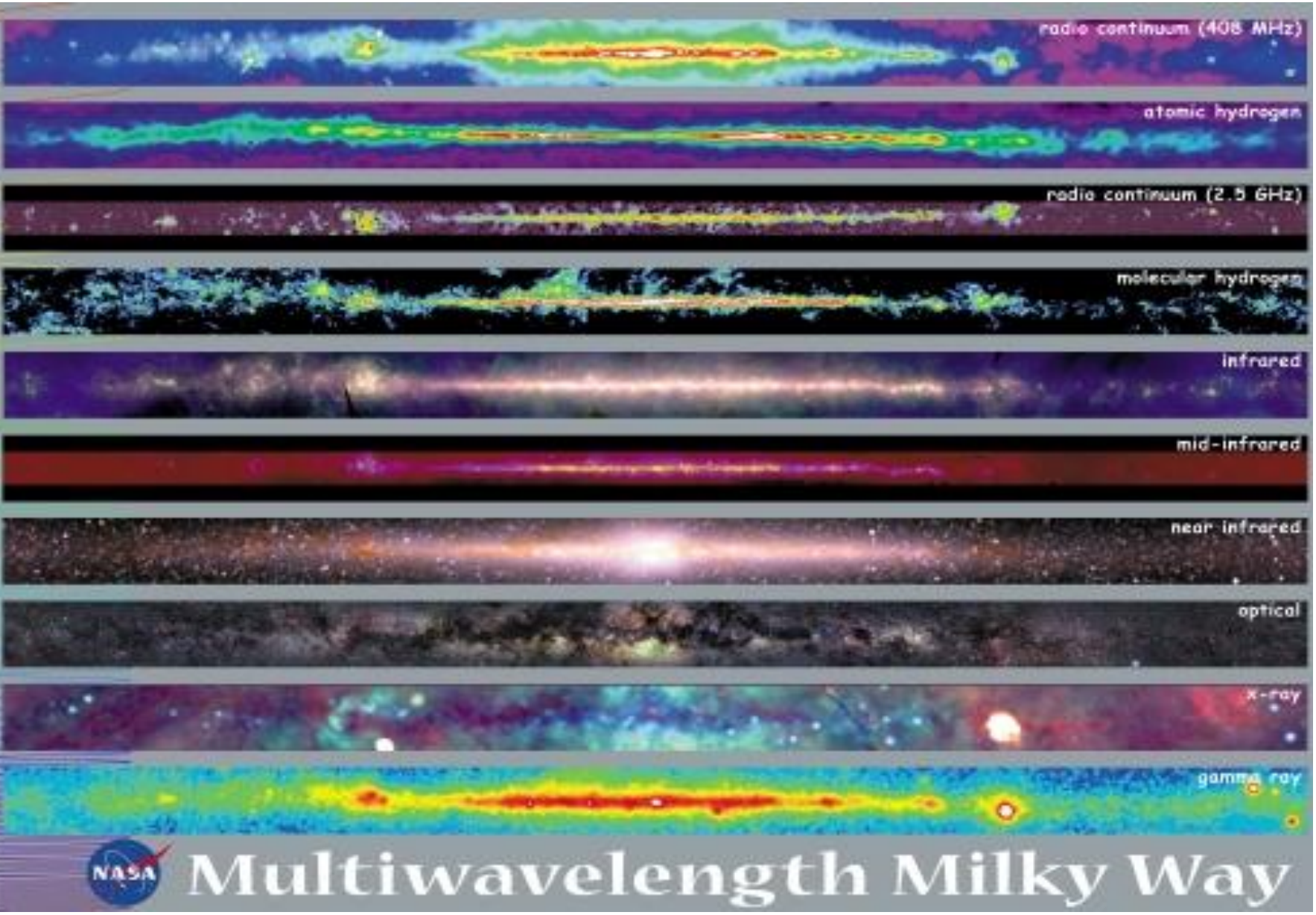
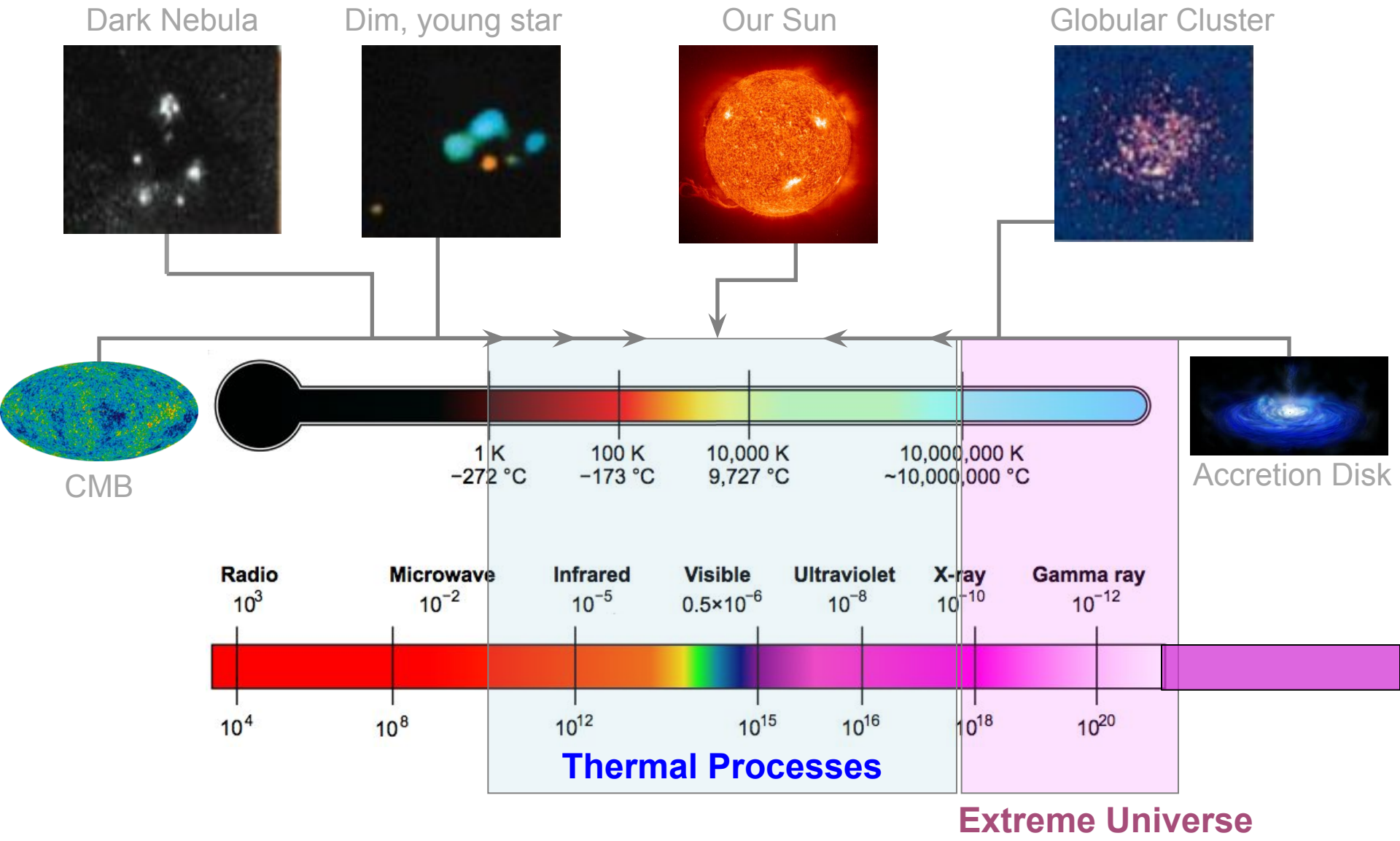
Different Wavelengths Probe Different Physics

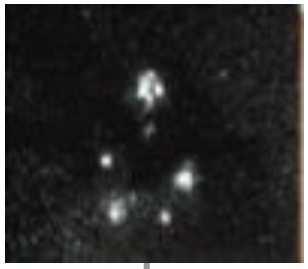


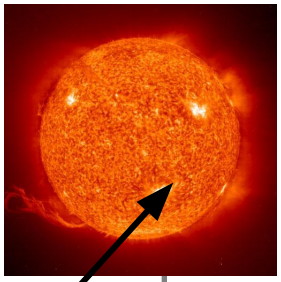
Gamma rays Probe the Extreme, Non-Thermal, Universe



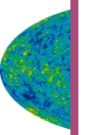
Gamma rays Probe the Extreme, Non-Thermal, Universe

Dark Nebula | Dim, young star | Our Sun | Globular Cluster

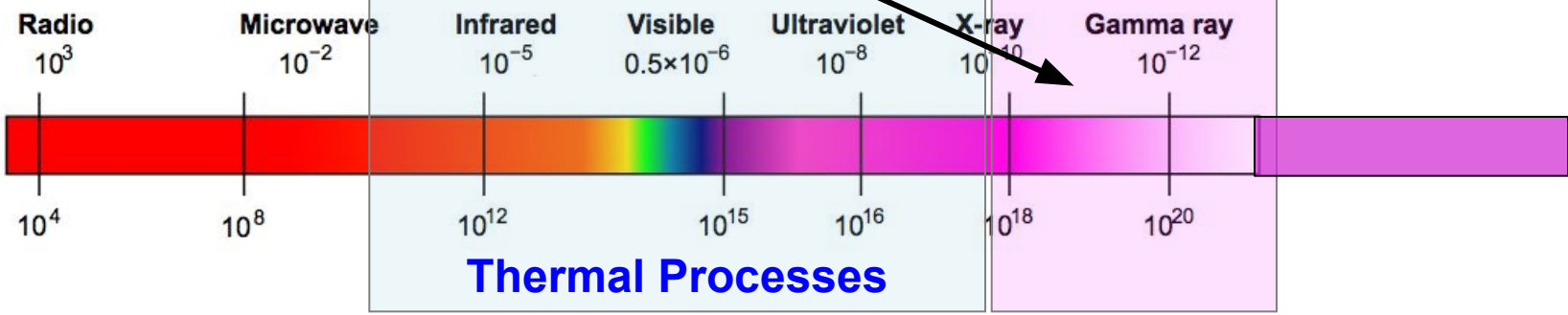





Visible photons E ~ 1 eV
Gamma-ray photons E ~ GeV (1,000,000,000 eV)


CMB

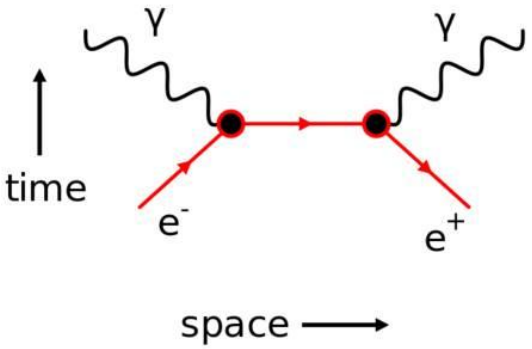

Accretion Disk



Non-thermal γ-ray Emission

Energy source

Acceleration mechanism

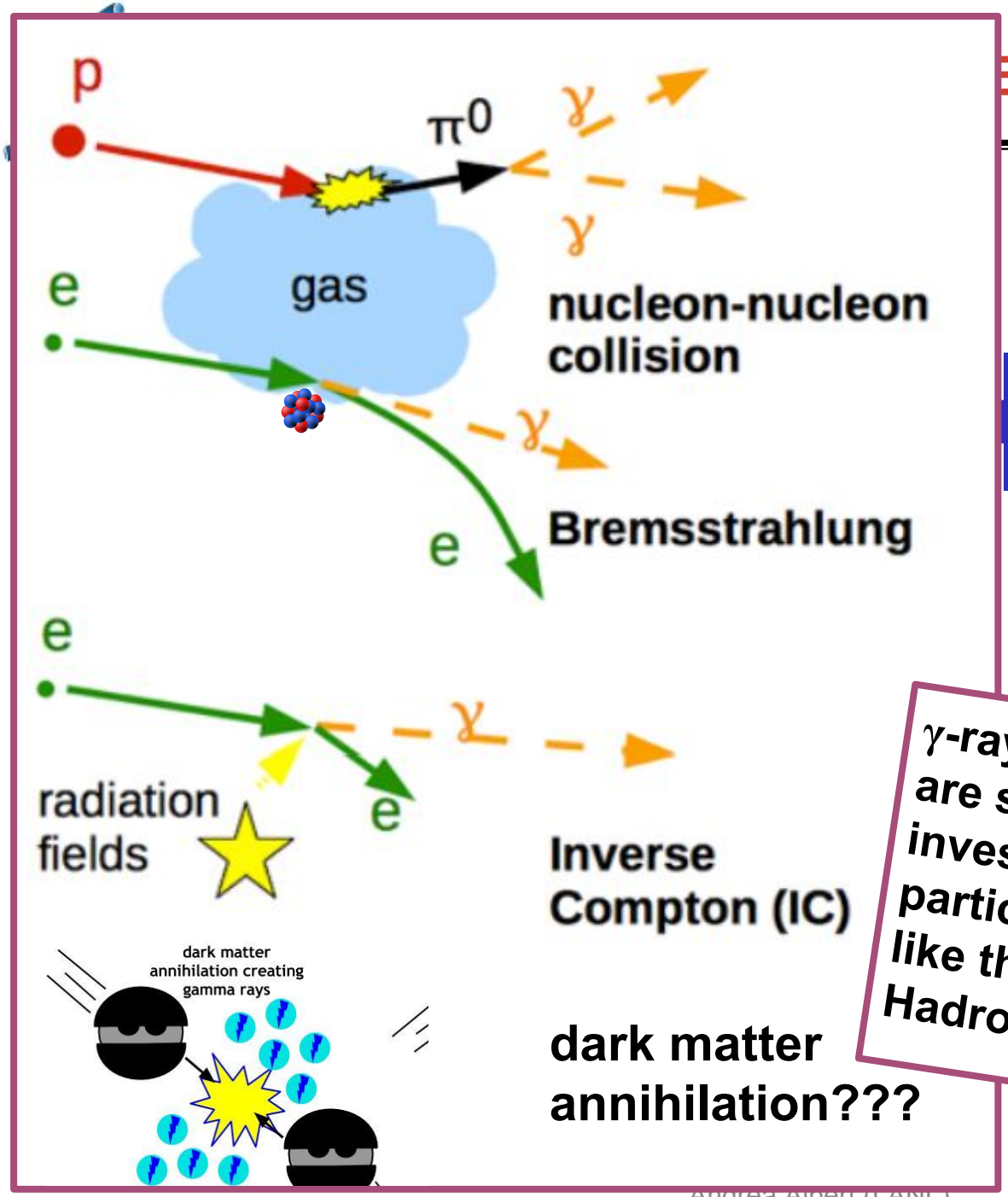


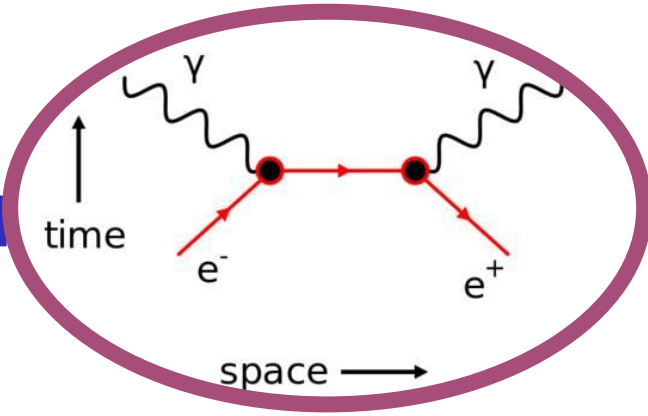
γ-ray production mechanism

Foreground absorption

γ rays

Emission

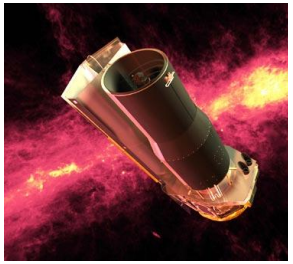


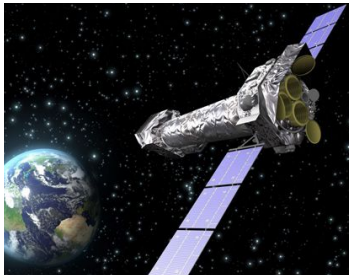
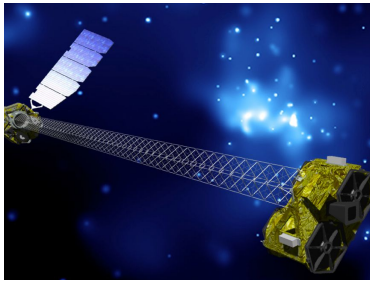


γ-ray production mechanism

γ-ray production mechanisms are similar to interactions investigated by high-energy particle physics experiments like those using the Large Hadron Collider

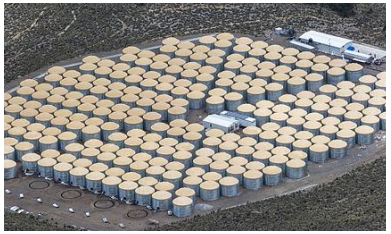
Different Wavelengths Require Different Telescope Technologies

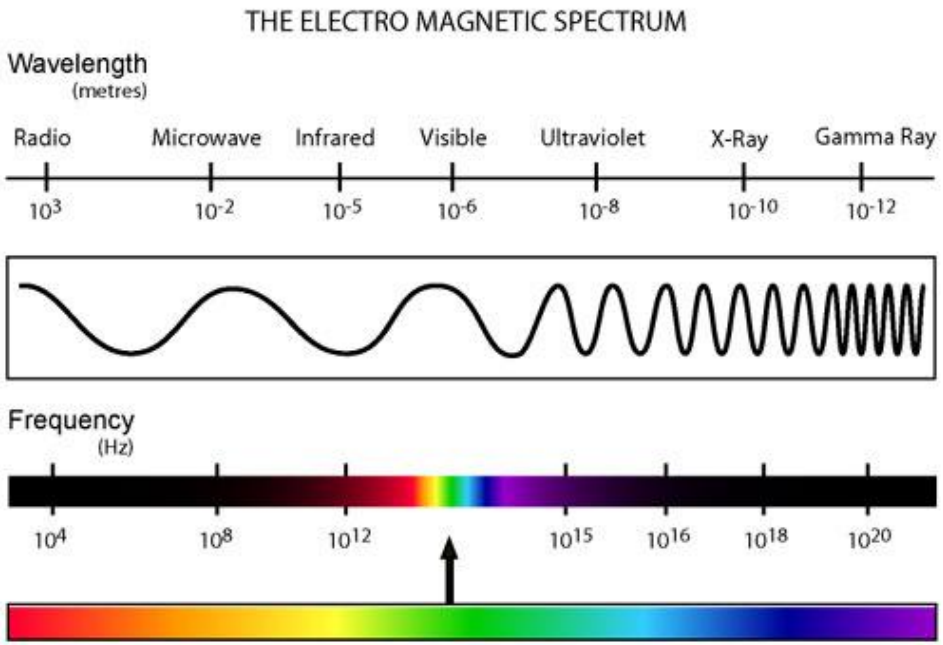











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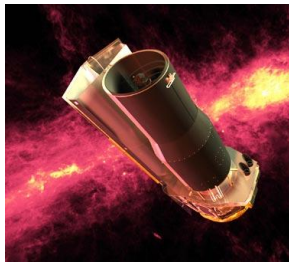
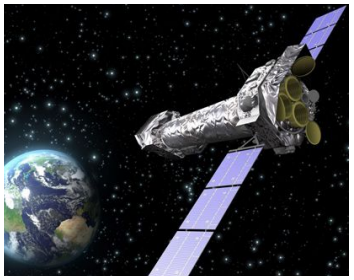
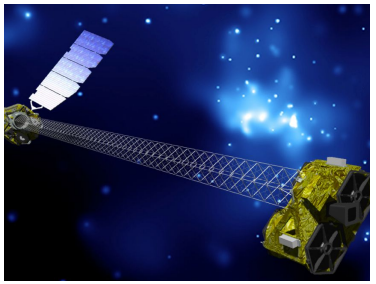
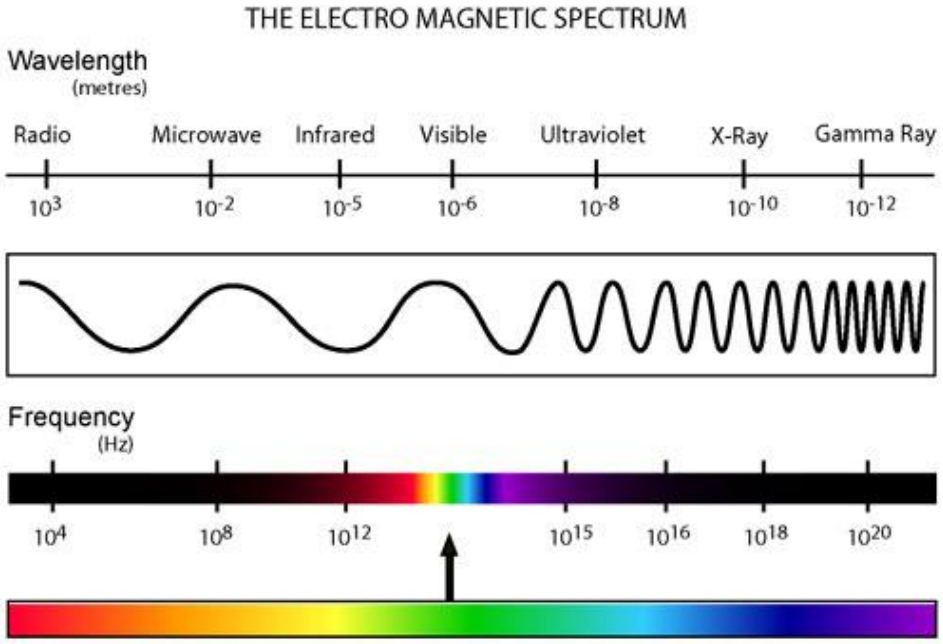


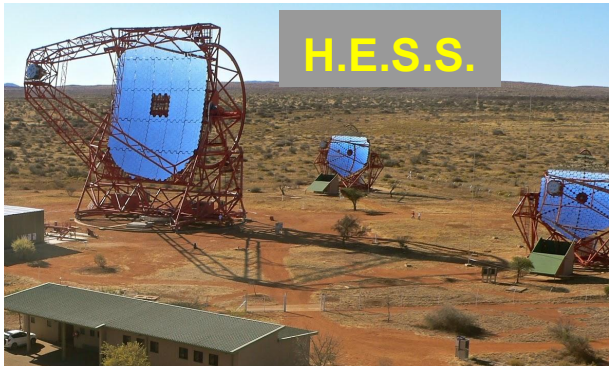






Current Gamma-ray Observatories

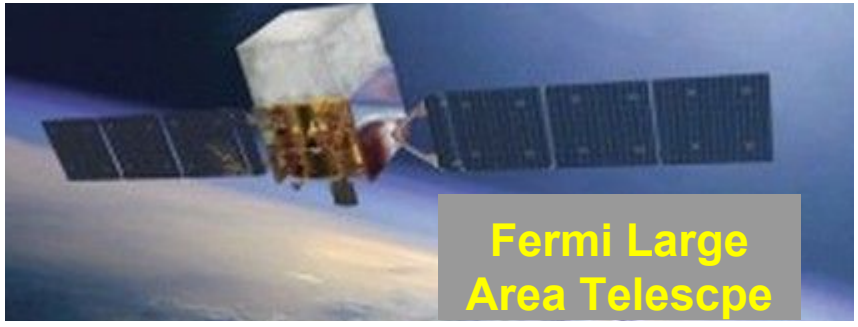
Tucson, Arizona
31° North Latitude, ~5° f.o.v.
~85 GeV -- ~50 TeV

La Palma, Canary Islands
29° North Latitude, ~5° f.o.v.
~30 GeV -- ~30 TeV



Khomas Highland of Namibia
23° South Latitude, ~5° f.o.v.
~30 GeV -- ~100 TeV

Parque Nacional Pico de Orizaba, Mexico
19° North Latitude, ~2 sr f.o.v.
~50 GeV -- ~100 TeV, ~100% Duty Cycle



Low earth orbit (565 km)
28.5° orbital inclination, ~2 sr f.o.v.
20 MeV -- > 300 GeV, ~100% Duty Cycle
(AGILE has similar technology, but has limited energy resolution)

Current Gamma-ray Observatories

Tucson, Arizona
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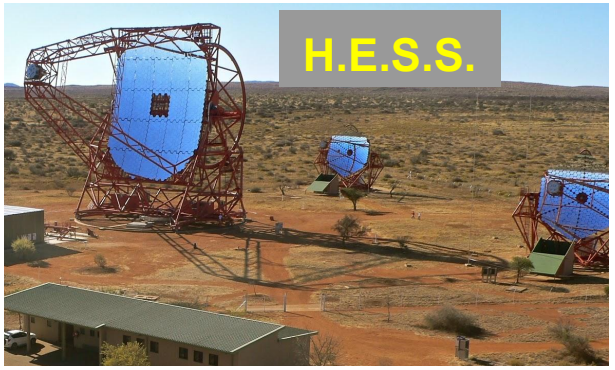


Khomas Highland of Namibia
23° South Latitude, ~5° f.o.v.
~30 GeV -- ~100 TeV

Air Cherenkov Telescopes (ACTs) have deeper exposure, better angular resolution, but smaller field of view and only operate at night in during good weather

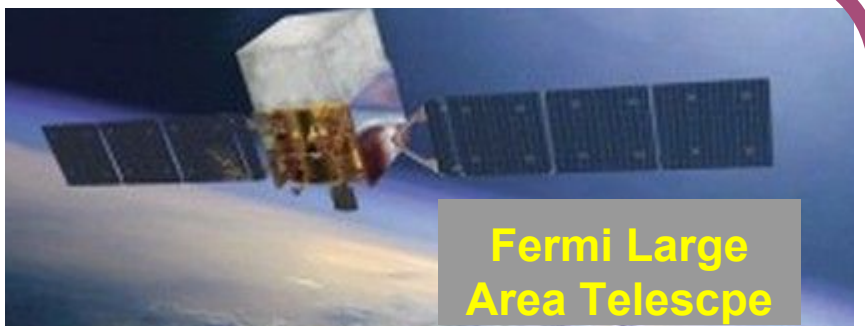
~50 GeV -- ~100 TeV, ~100% Duty Cycle

limited energy resolution)

Current Gamma-ray Observatories

HAWC (~1 TeV) and Fermi LAT (~1 GeV) are complementary wide field of view survey instruments. Provide continuous monitoring of the gamma-ray sky across 7 decades of energy (20 MeV to >100 TeV)

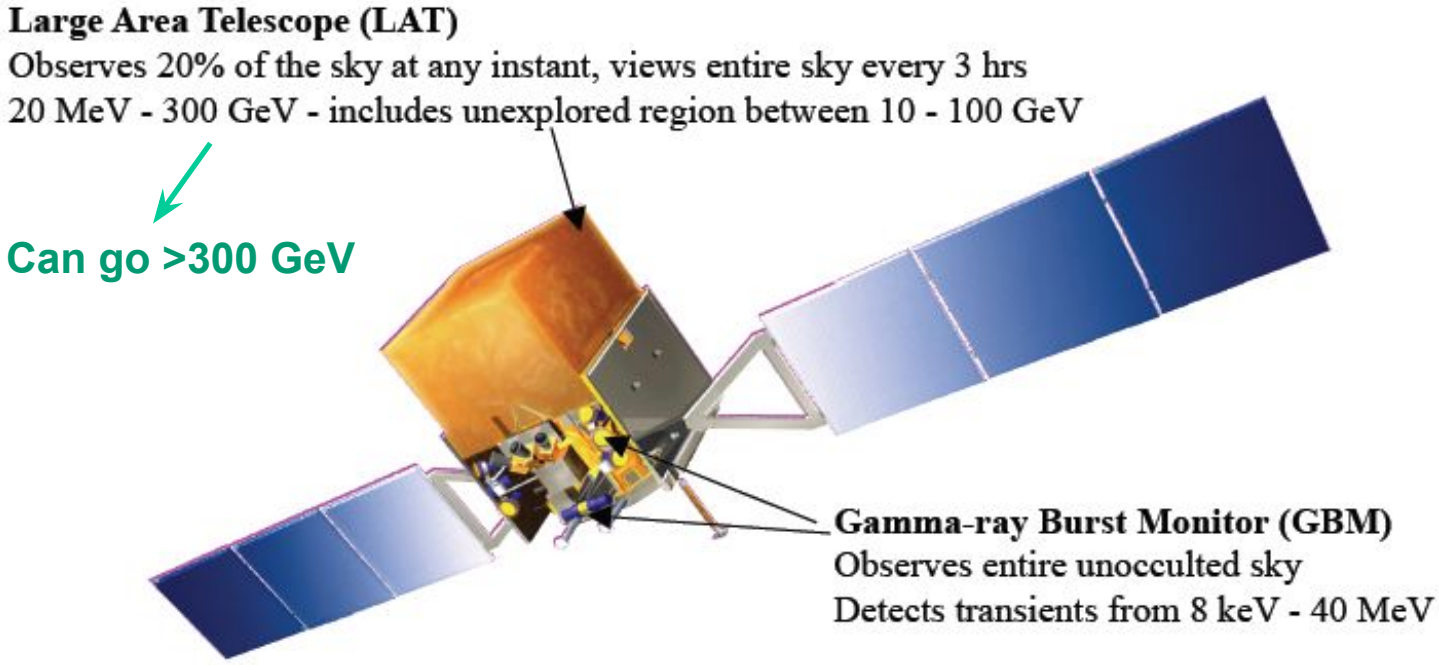
Parque Nacional Pico de Orizaba, Mexico
19° North Latitude, ~2 sr f.o.v.
~50 GeV -- ~100 TeV, ~100% Duty Cycle



Low earth orbit (565 km)
28.5° orbital inclination, ~2 sr f.o.v.
20 MeV -- > 300 GeV, ~100% Duty Cycle
(AGILE has similar technology, but has limited energy resolution)

Fermi Large Area Telescope (LAT)

- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008 (science mission started Aug. 2008)**
    - **Mission extended at least through 2018**
    - **No consumables**
      - **Orbit re-entry expected ~2026-2044 (depending on solar activity)**
  - **LAT has triggered on ~500 billion events**
    - **Processed ~100 billion events (>1 Petabyte!)**



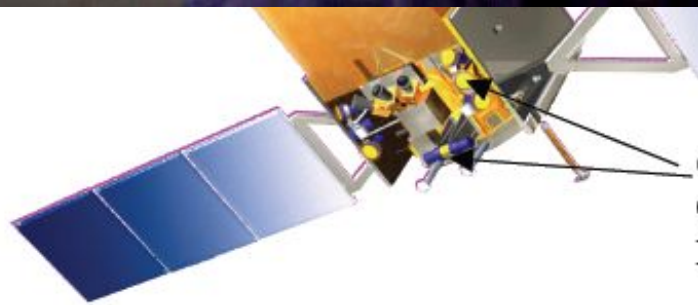
Fermi Large Area Telescope (LAT)

- On
  - – Aug. 2008)
  - – on solar activity)

Large
Observ
20 Me

Can g

my Ph.D. adviser Dr. Brian Winer got his facebook profile pic at launch



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

Fermi Large Area Telescope (LAT)

NASA/Kim Shiflett

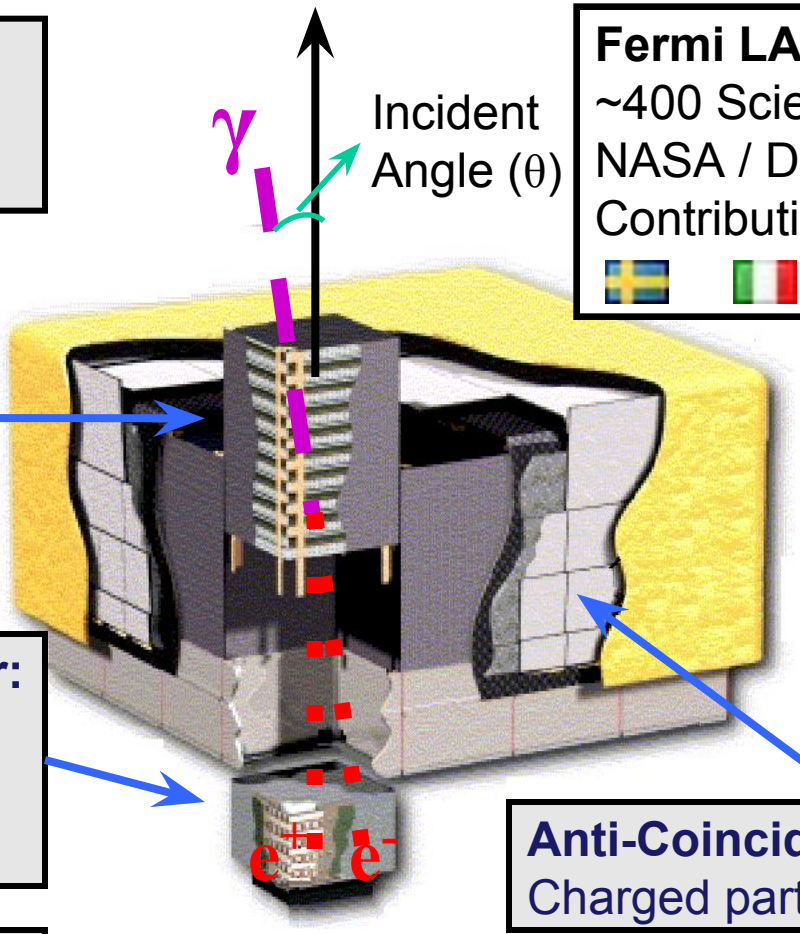
Fermi LAT

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Si-Strip Tracker:
convert γ->e^+e^-
reconstruct γ direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

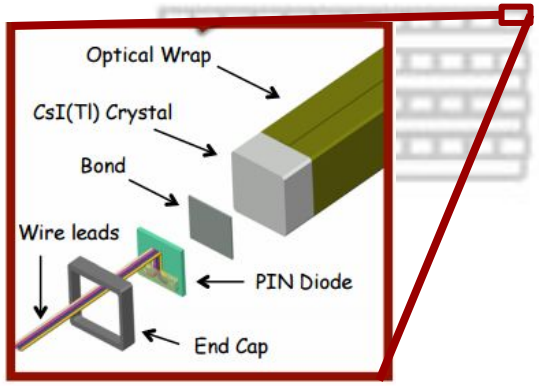
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz



Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

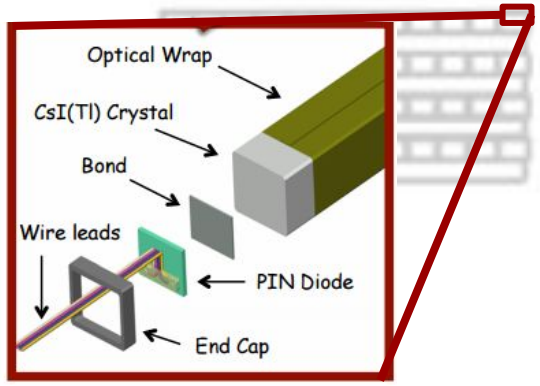
Anti-Coincidence Detector:
Charged particle separation

Simulated 27 GeV Gamma-ray Event



Incoming γ-ray direction

Simulated 27 GeV Gamma-ray Event



Incoming γ-ray direction

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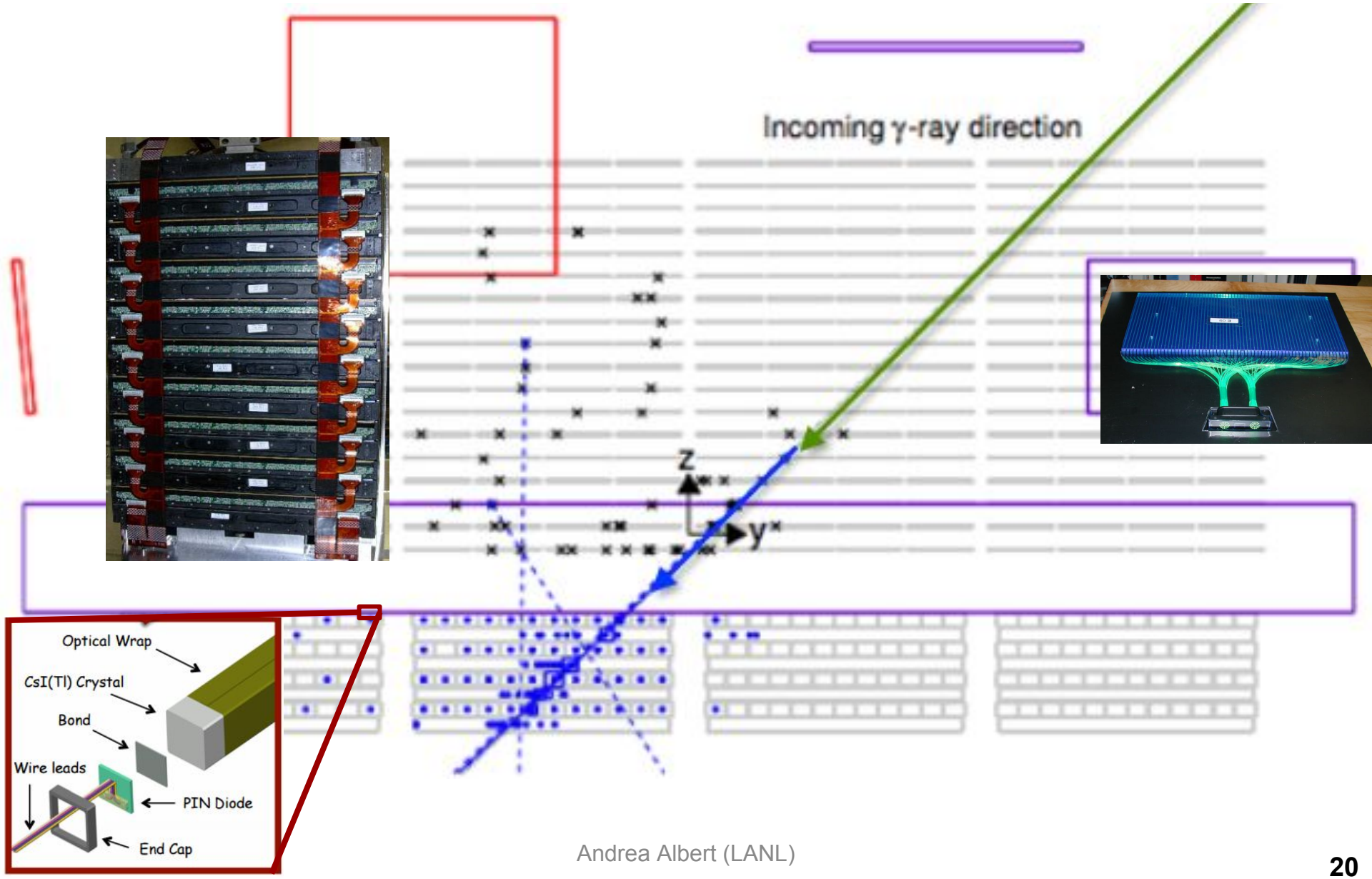
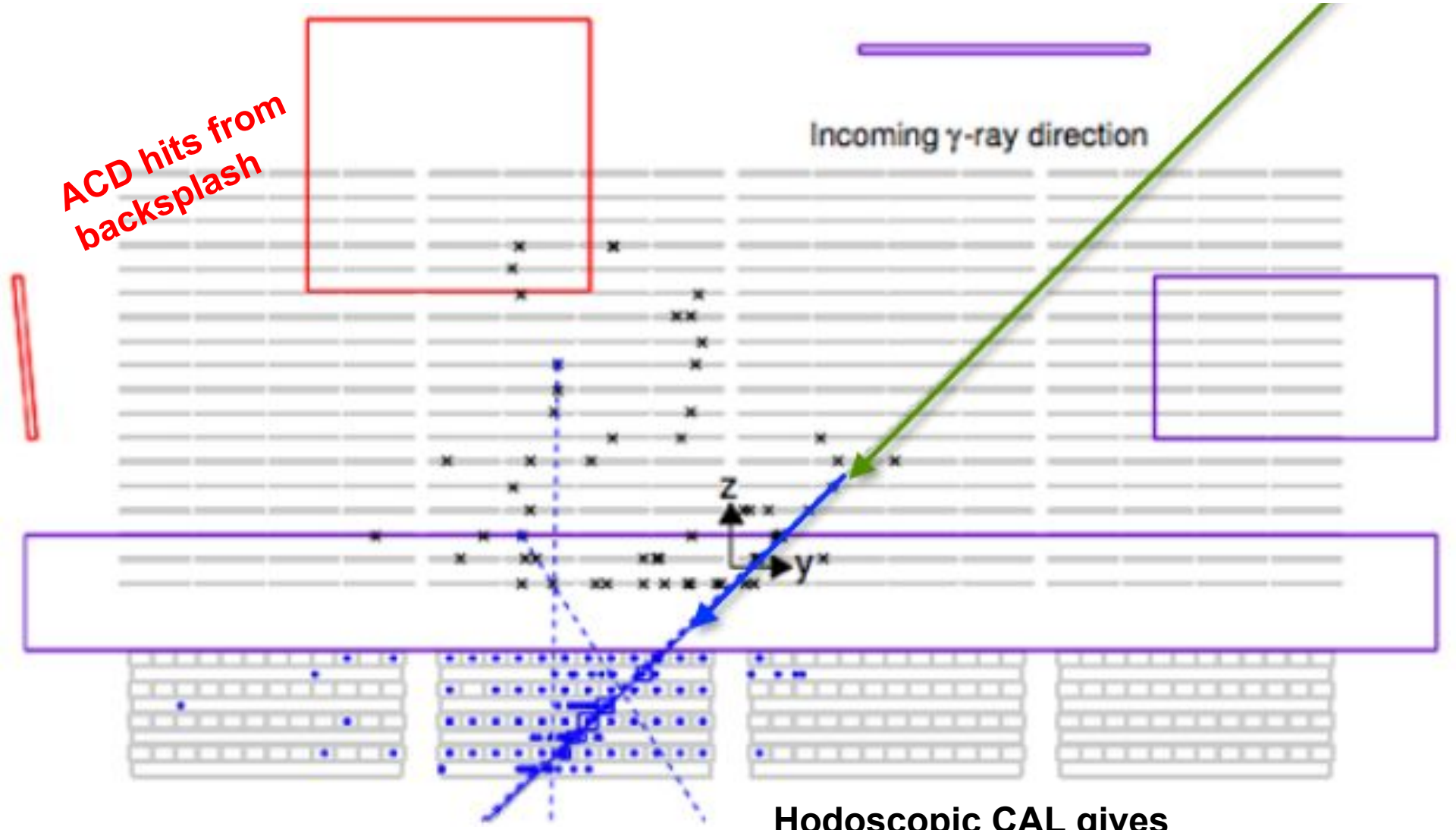
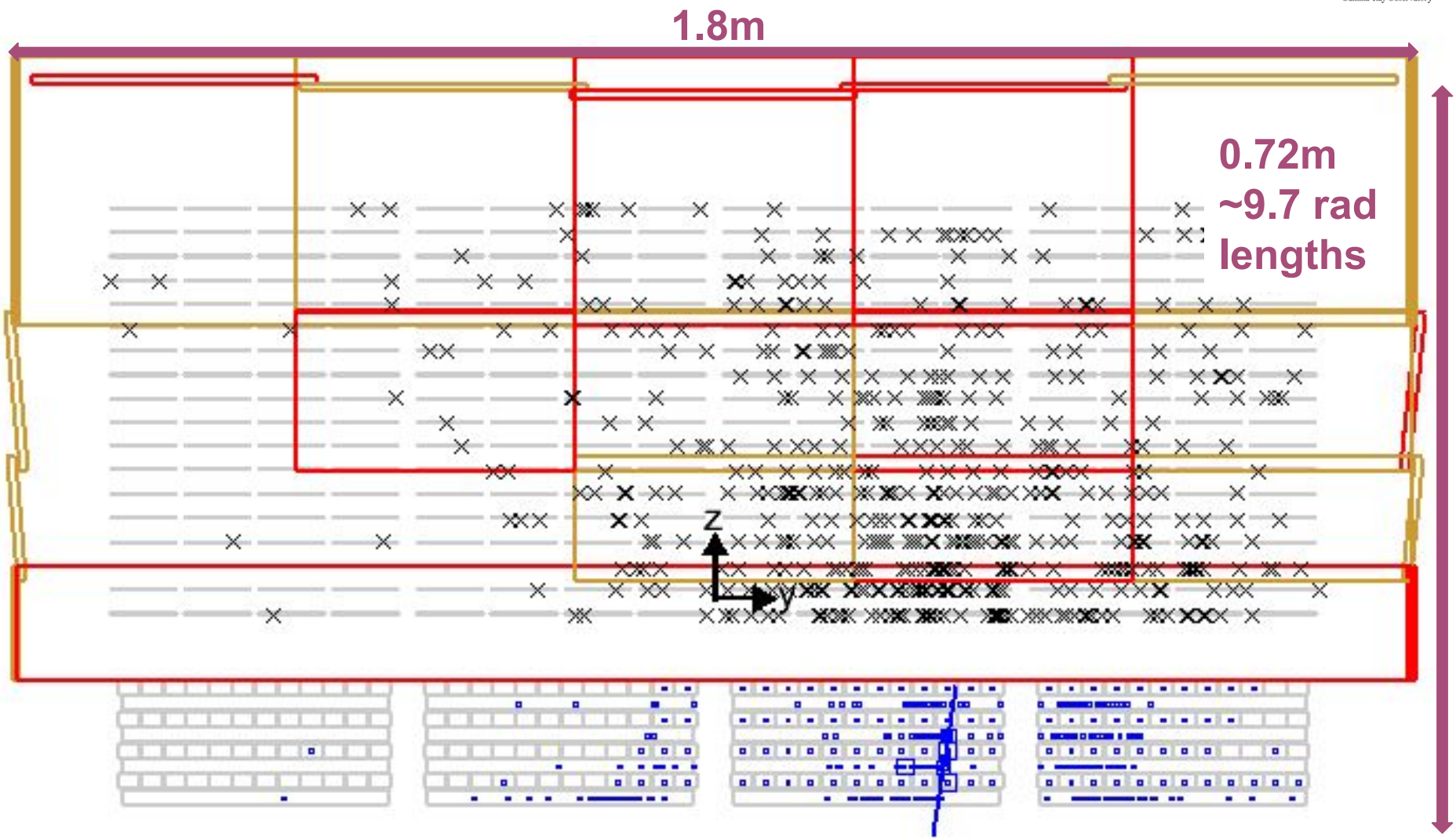


Simulated 27 GeV Gamma-ray Event



Hodoscopic CAL gives provides 3D directional info

LAT Simulated 1 TeV Gamma-ray Event



The HAWC Observatory

Joint NSF/DOE/CONACyT (Mexico)

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

Pico de Orizaba
(5,626 m)

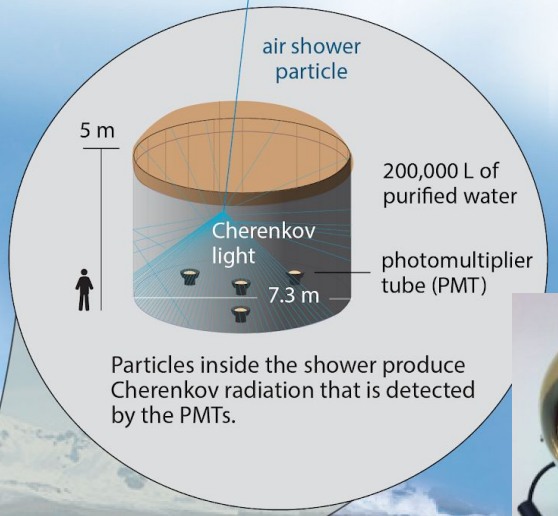
~17 rad lengths

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m^2.

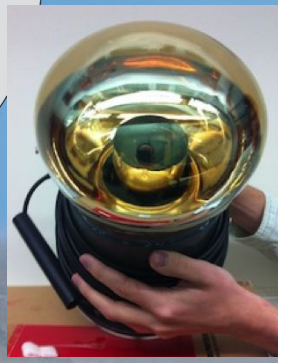
150 m

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



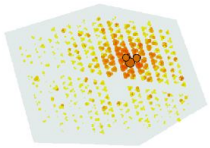
Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.



Gamma rays vs cosmic rays

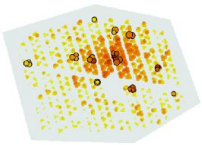
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



"hot" spots concentrate around the core

cosmic-ray shower



"hot" spots are more dispersed

Andrea Albert (LANL)

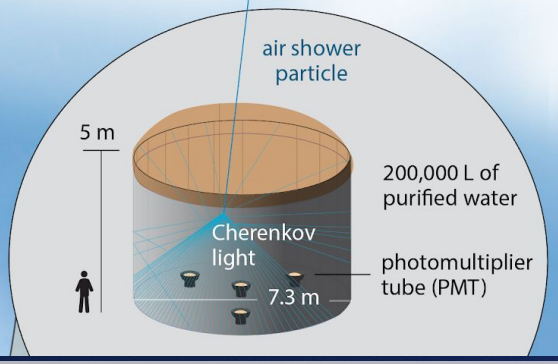
The HAWC Observatory

Joint NSF/DOE/CONACyT (Mexico)

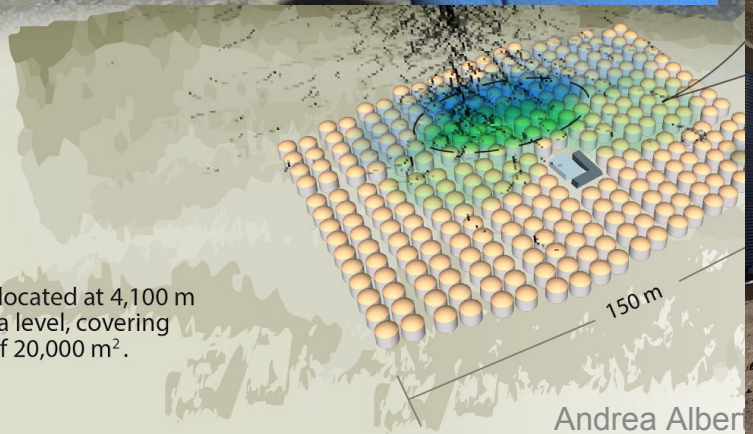
current supervisor's facebook profile pic (Dr. Brenda Dingus)

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



My colleague Kelly Malone (graduate student at Penn State)



HAWC is located at 4,100 m above sea level, covering an area of 20,000 m^2.

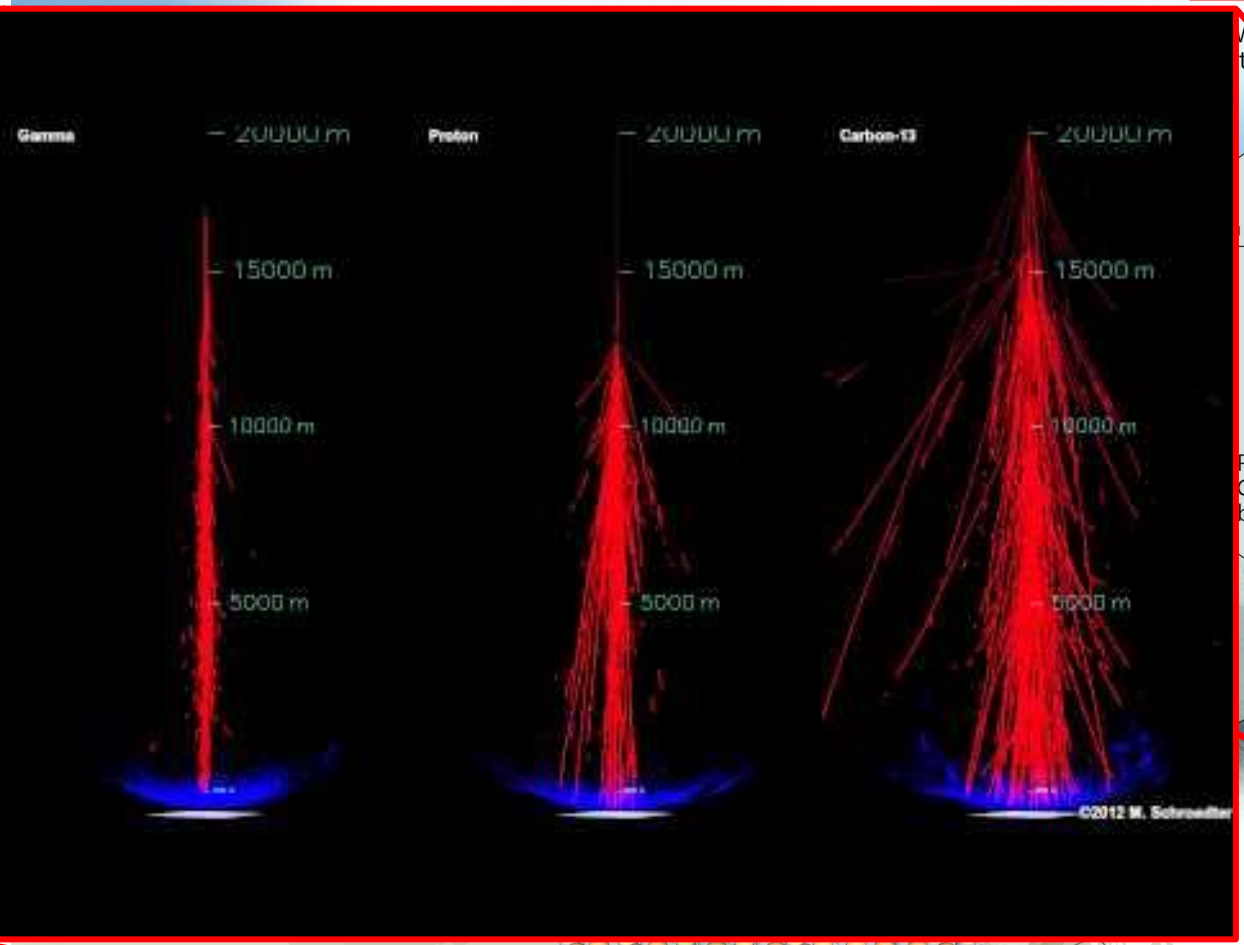
Andrea Albert

h more

ower

more

The HAWC Observatory



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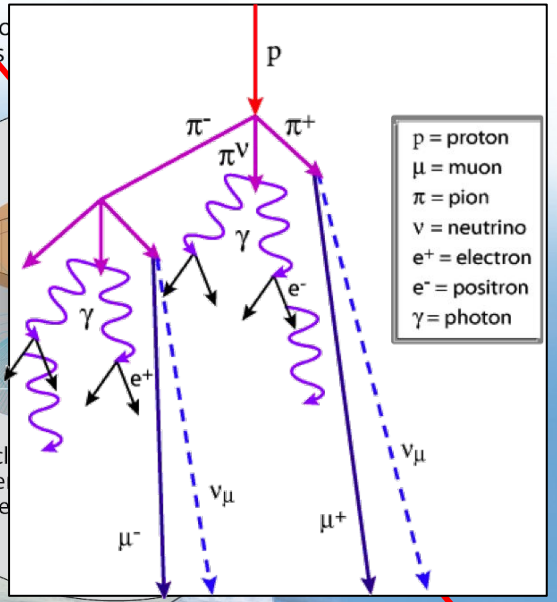

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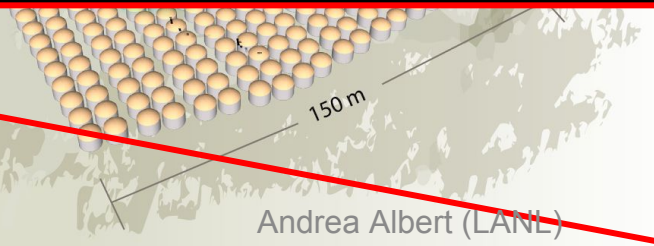
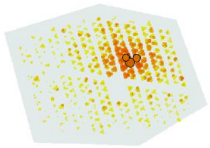
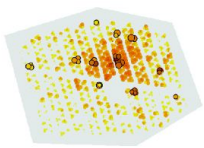


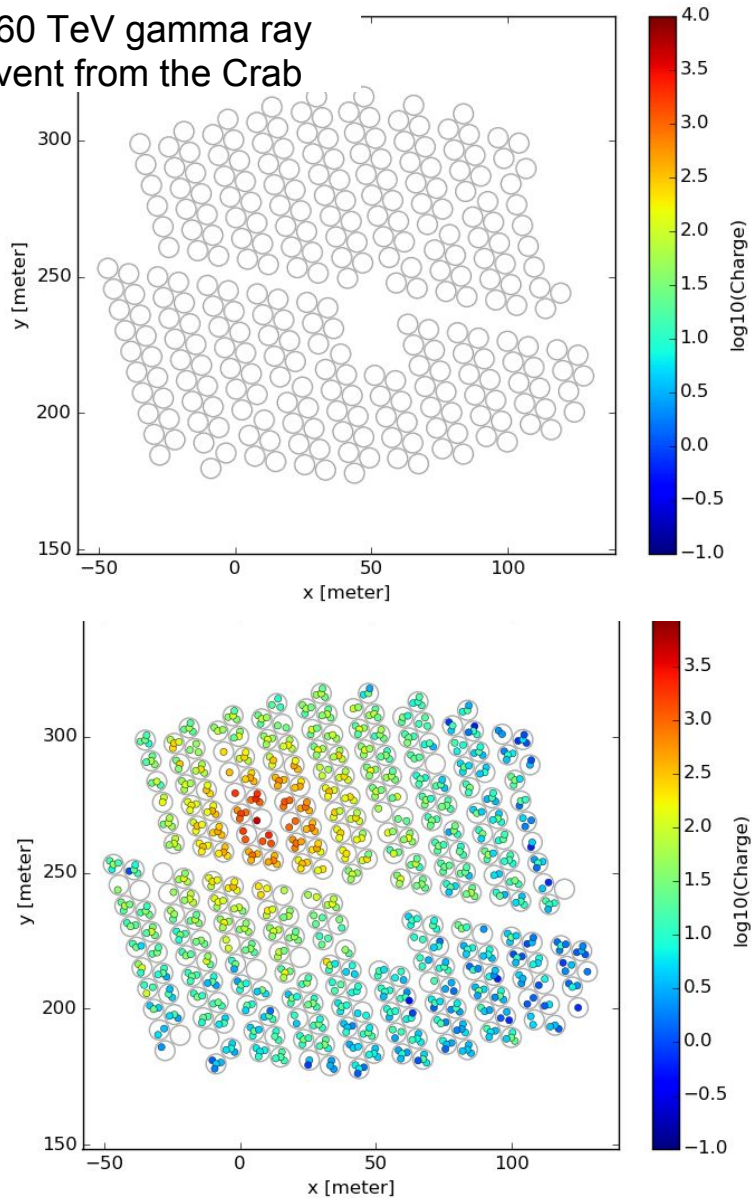
Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower	cosmic-ray shower
	
"hot" spots concentrate around the core	"hot" spots are more dispersed

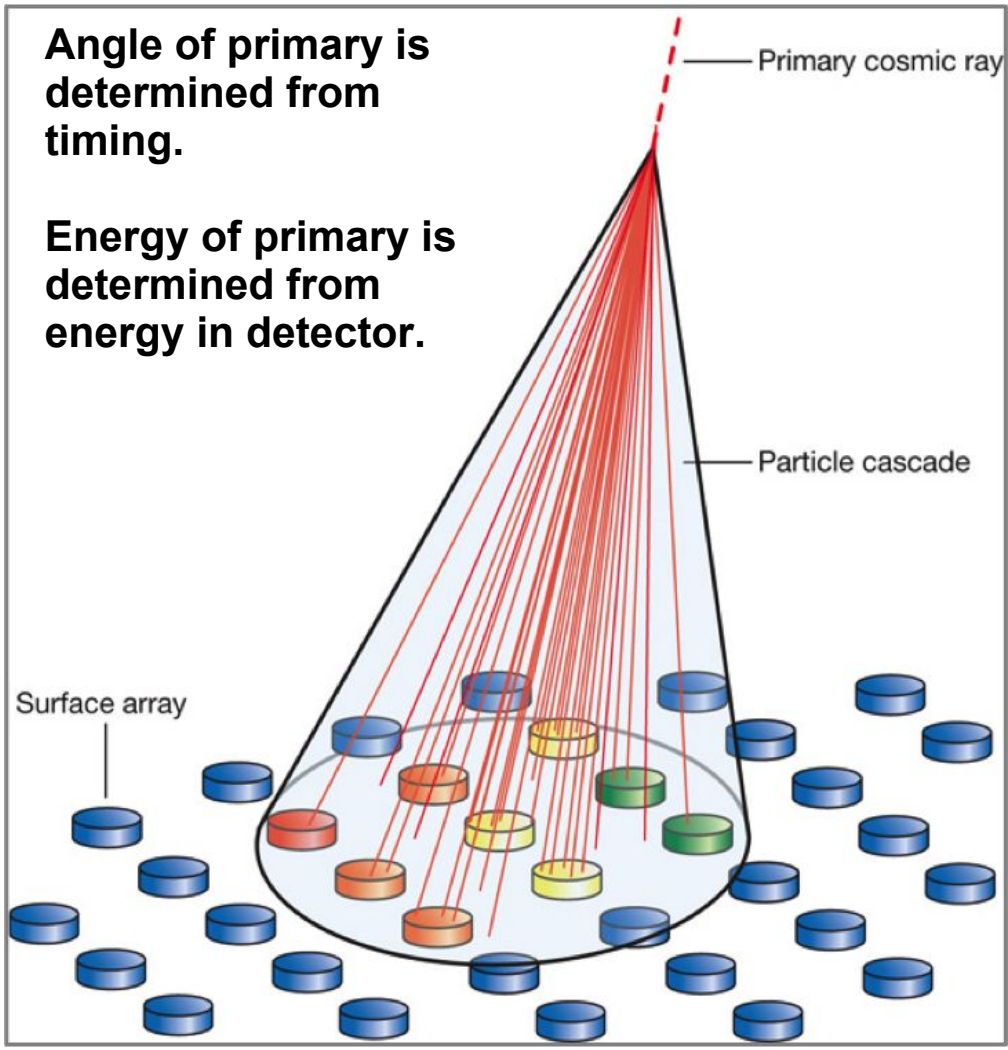
The HAWC Observatory

~60 TeV gamma ray event from the Crab



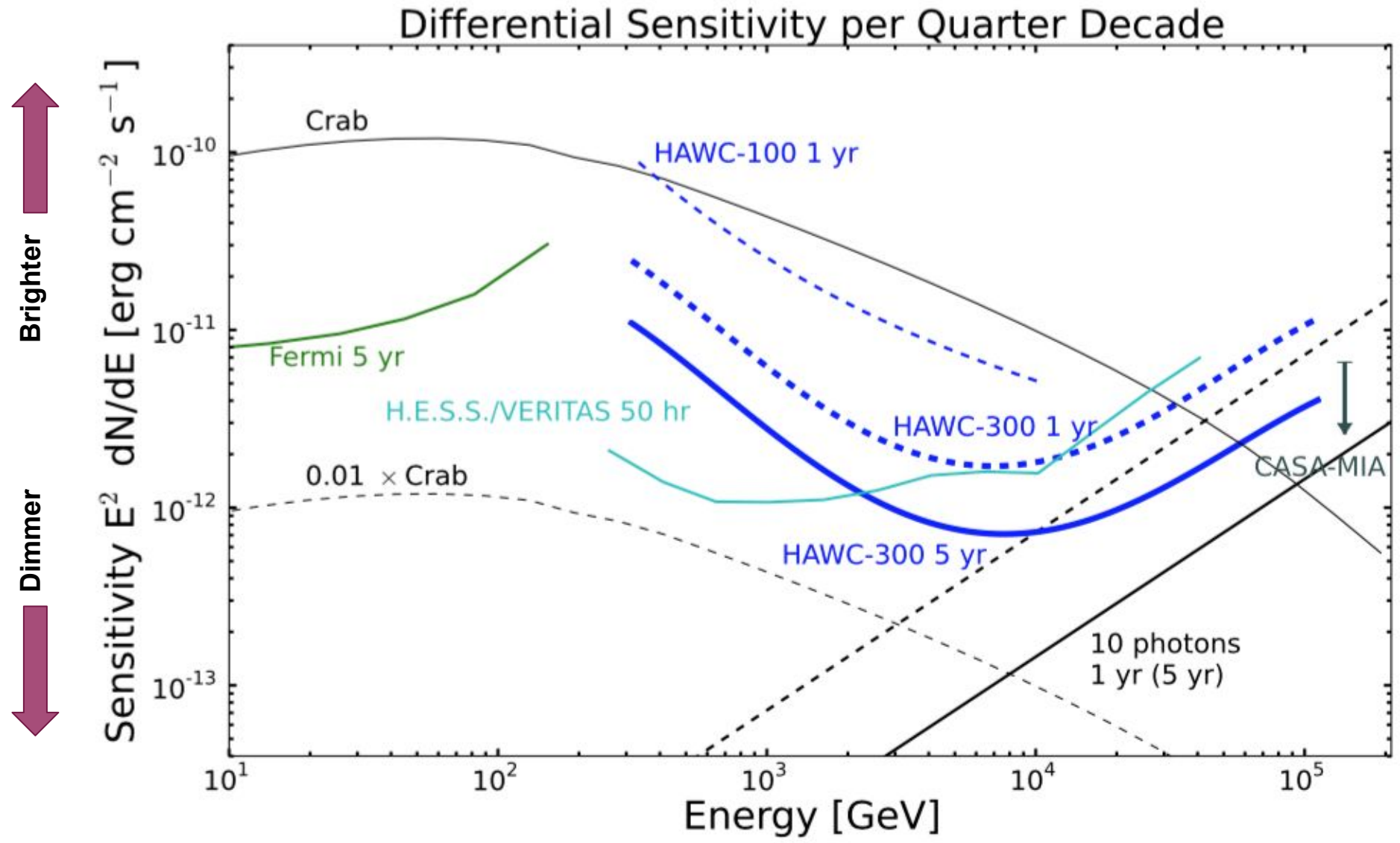
Angle of primary is determined from timing.

Energy of primary is determined from energy in detector.



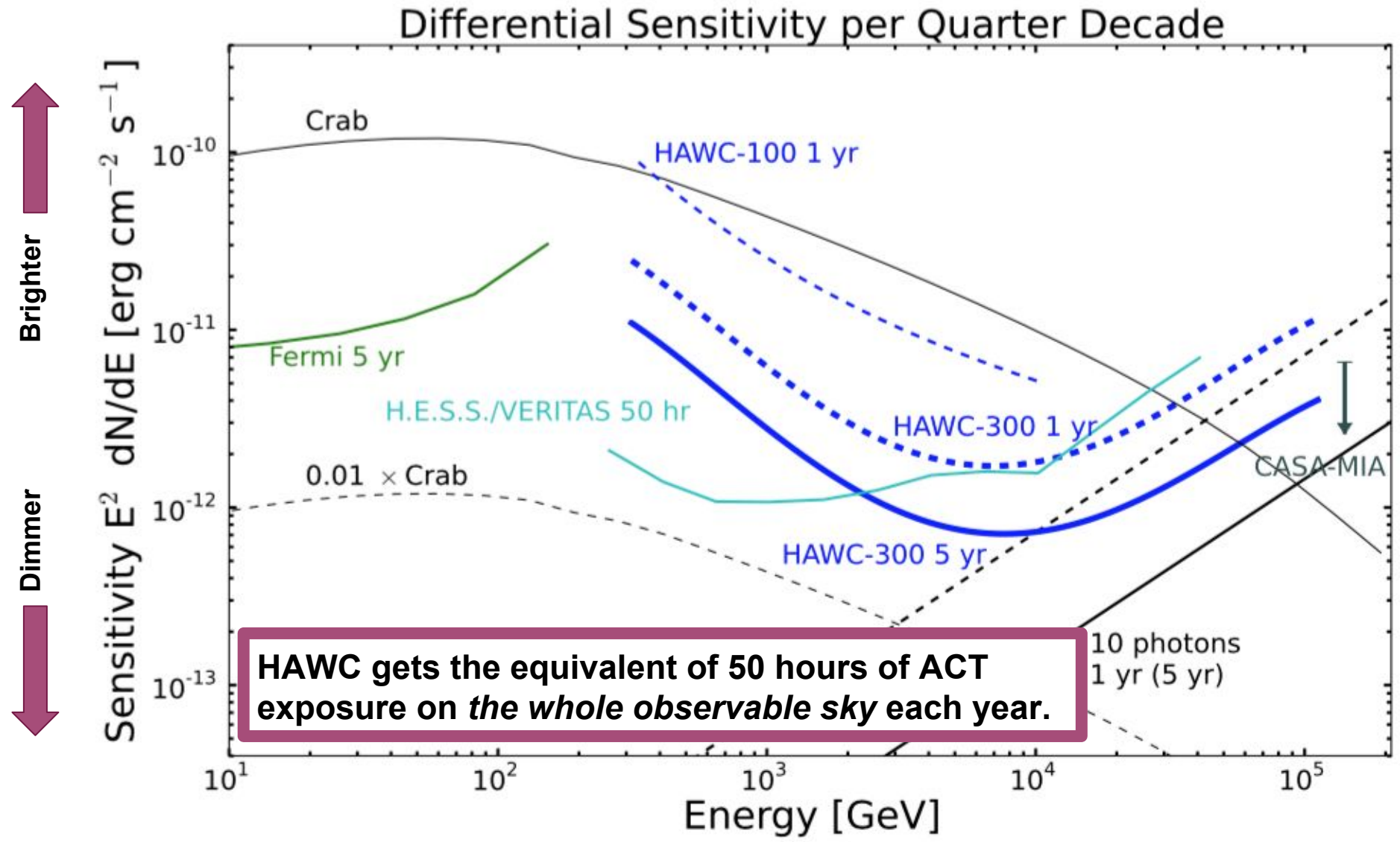
gamma ray event movie by John Pretz

Complementary Sensitivity



arXiv:1306.5800

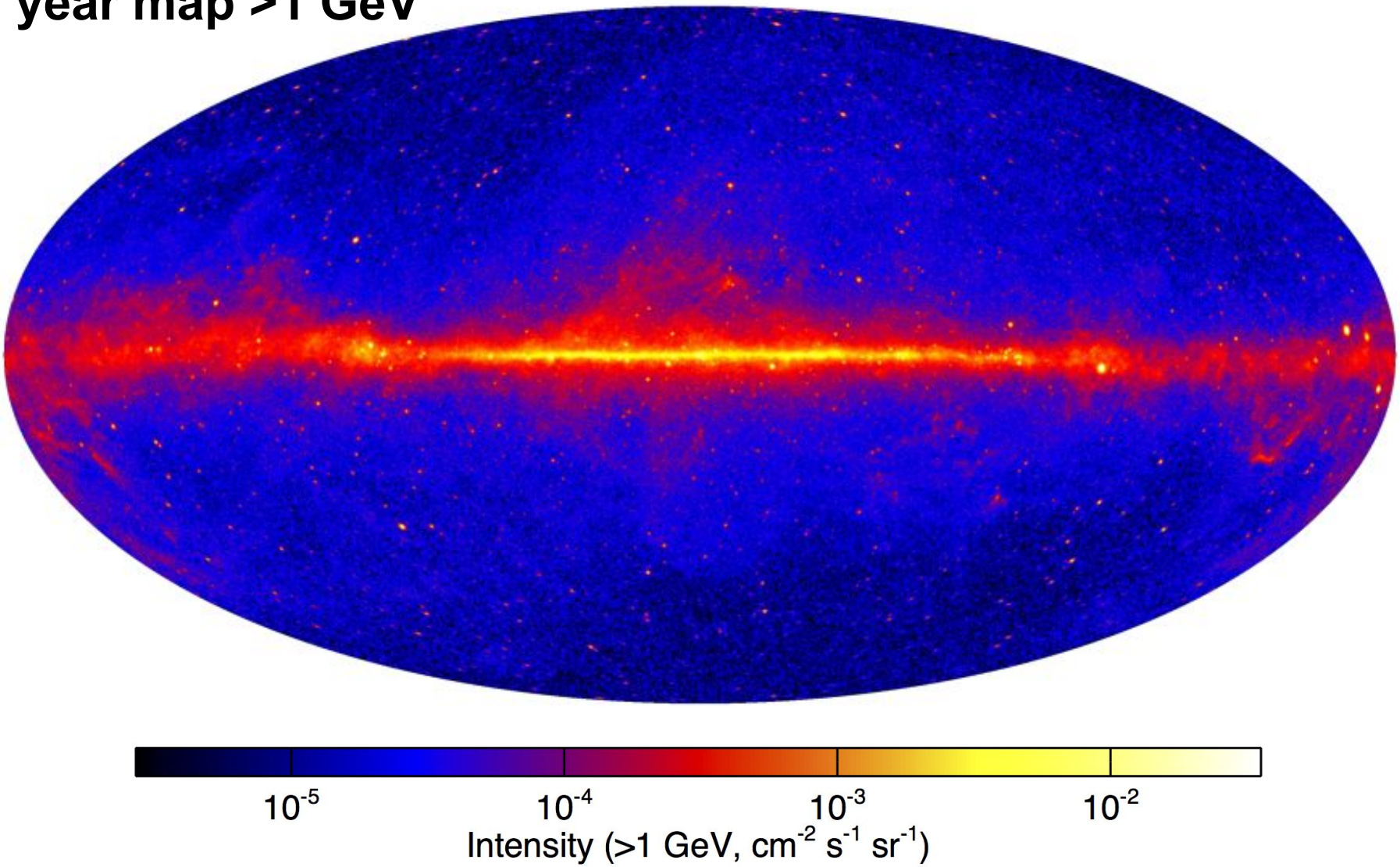
Complementary Sensitivity



arXiv:1306.5800

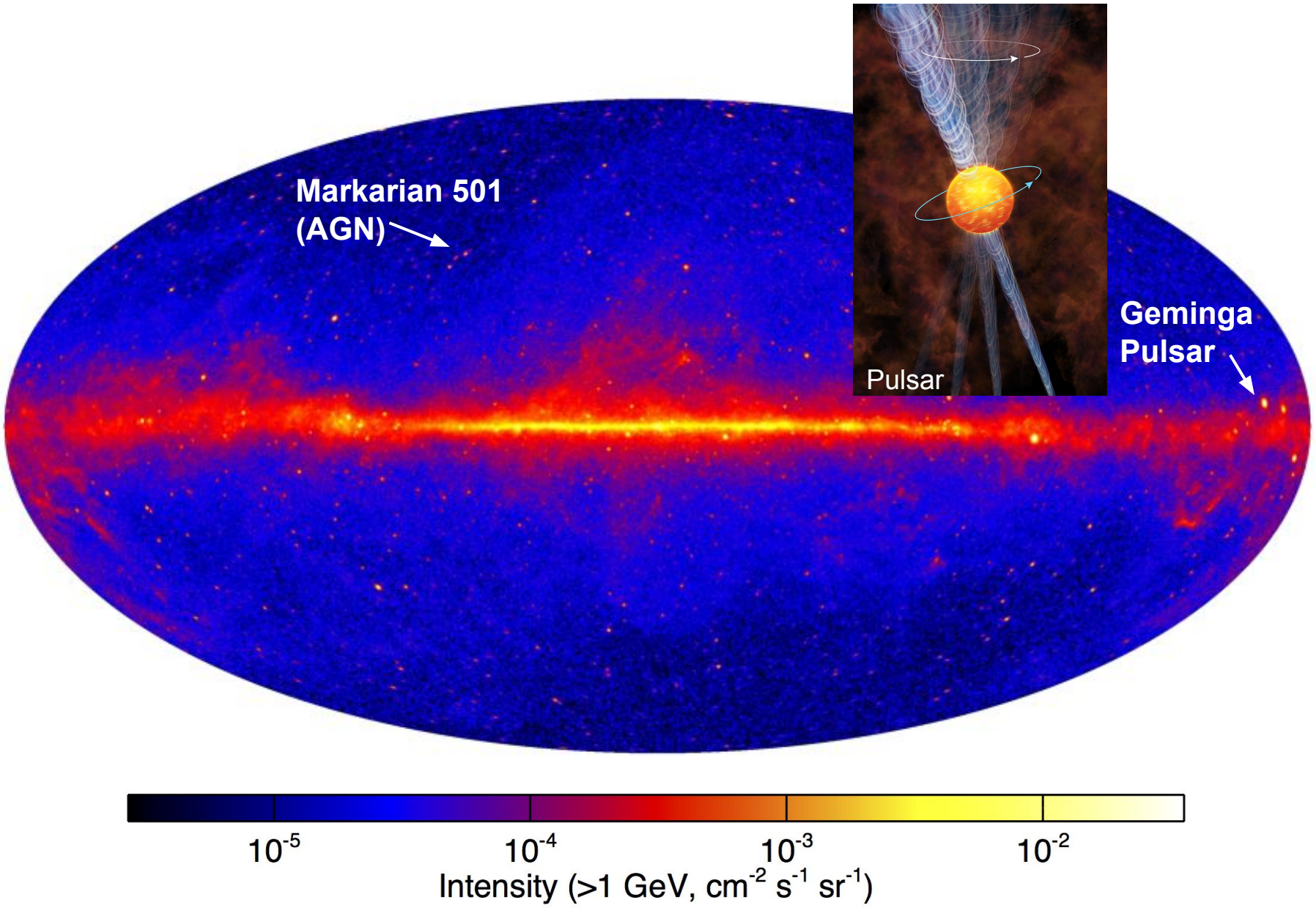
Fermi LAT GeV Gamma-ray Sky

Fermi Large Area Telescope
7 year map >1 GeV

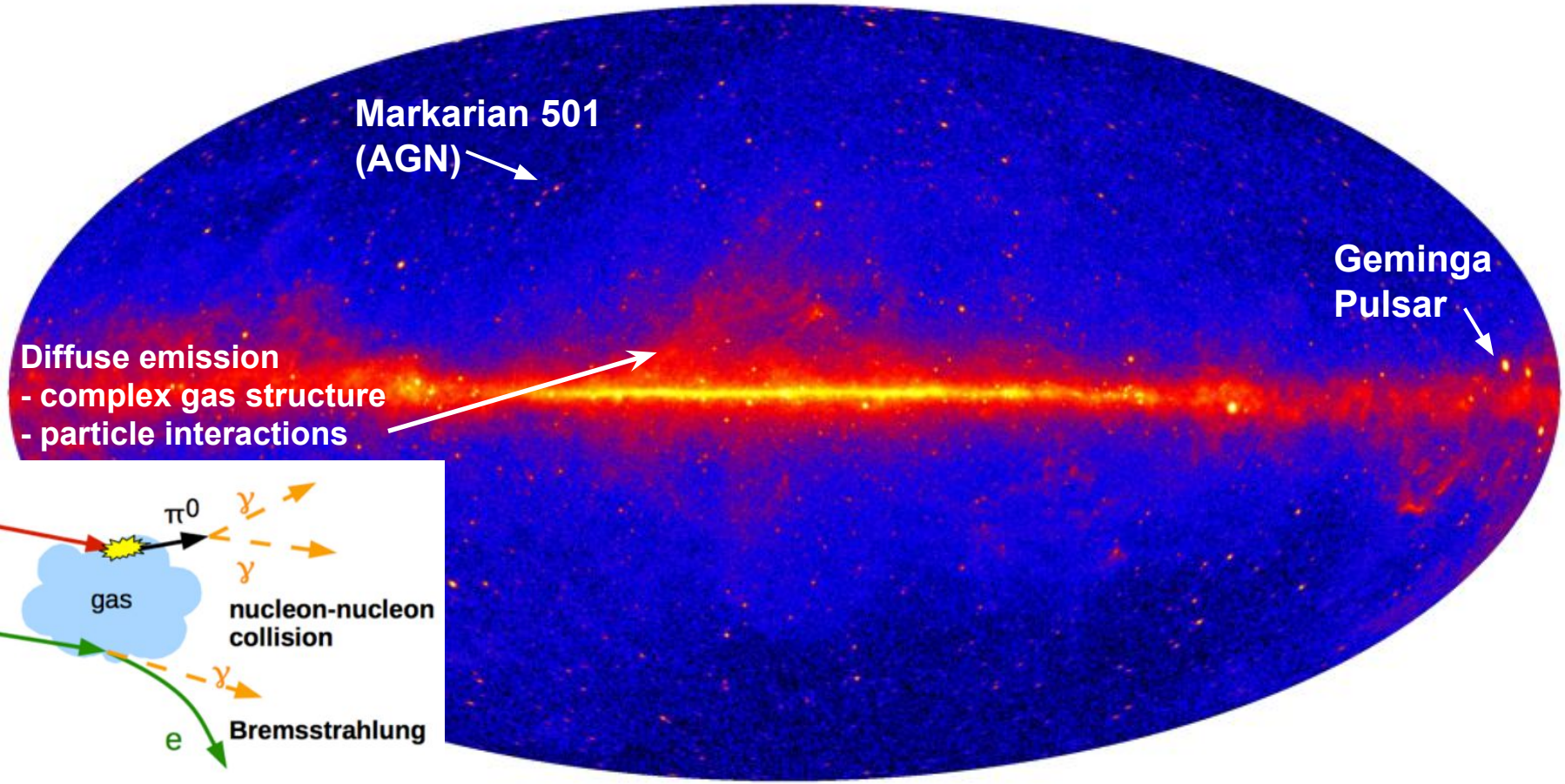


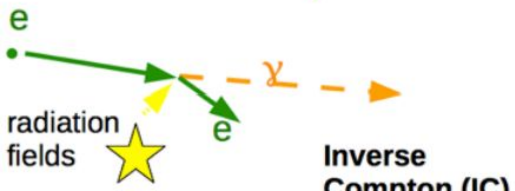
Fermi LAT GeV Gamma-ray Sky

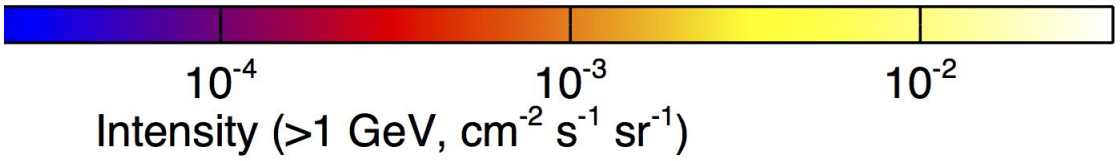
Fermi LAT GeV Gamma-ray Sky



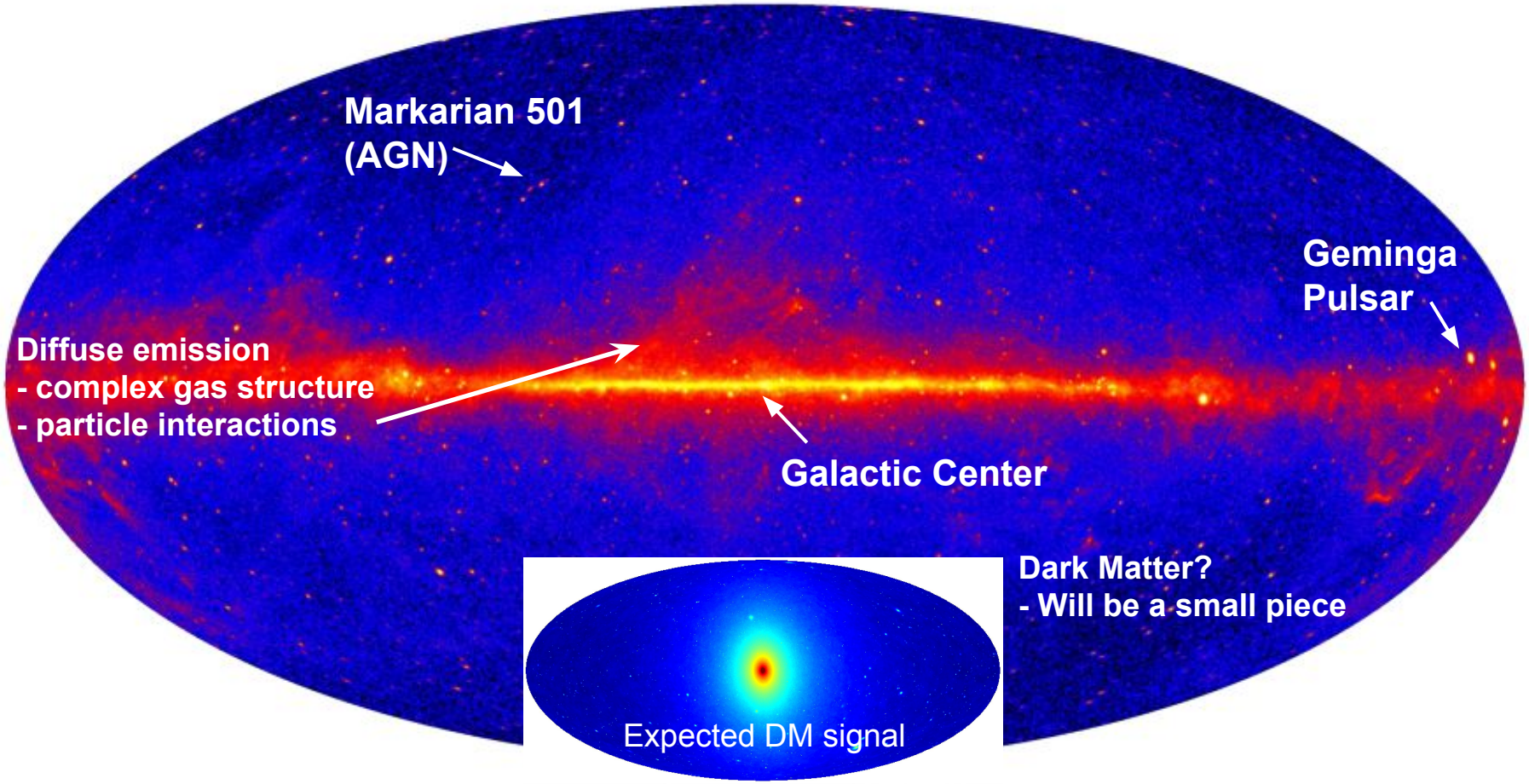
Fermi LAT GeV Gamma-ray Sky



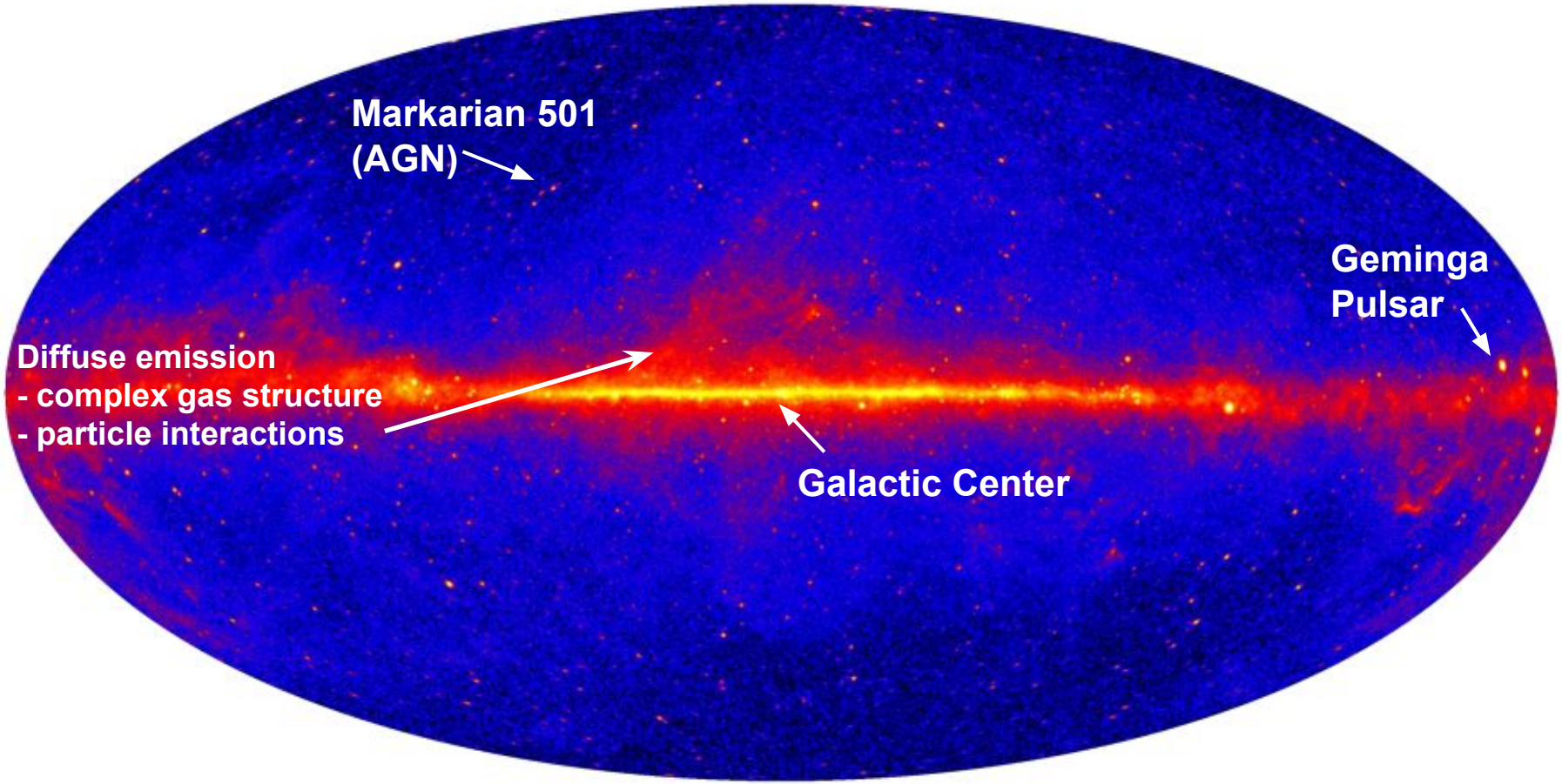




Fermi LAT GeV Gamma-ray Sky

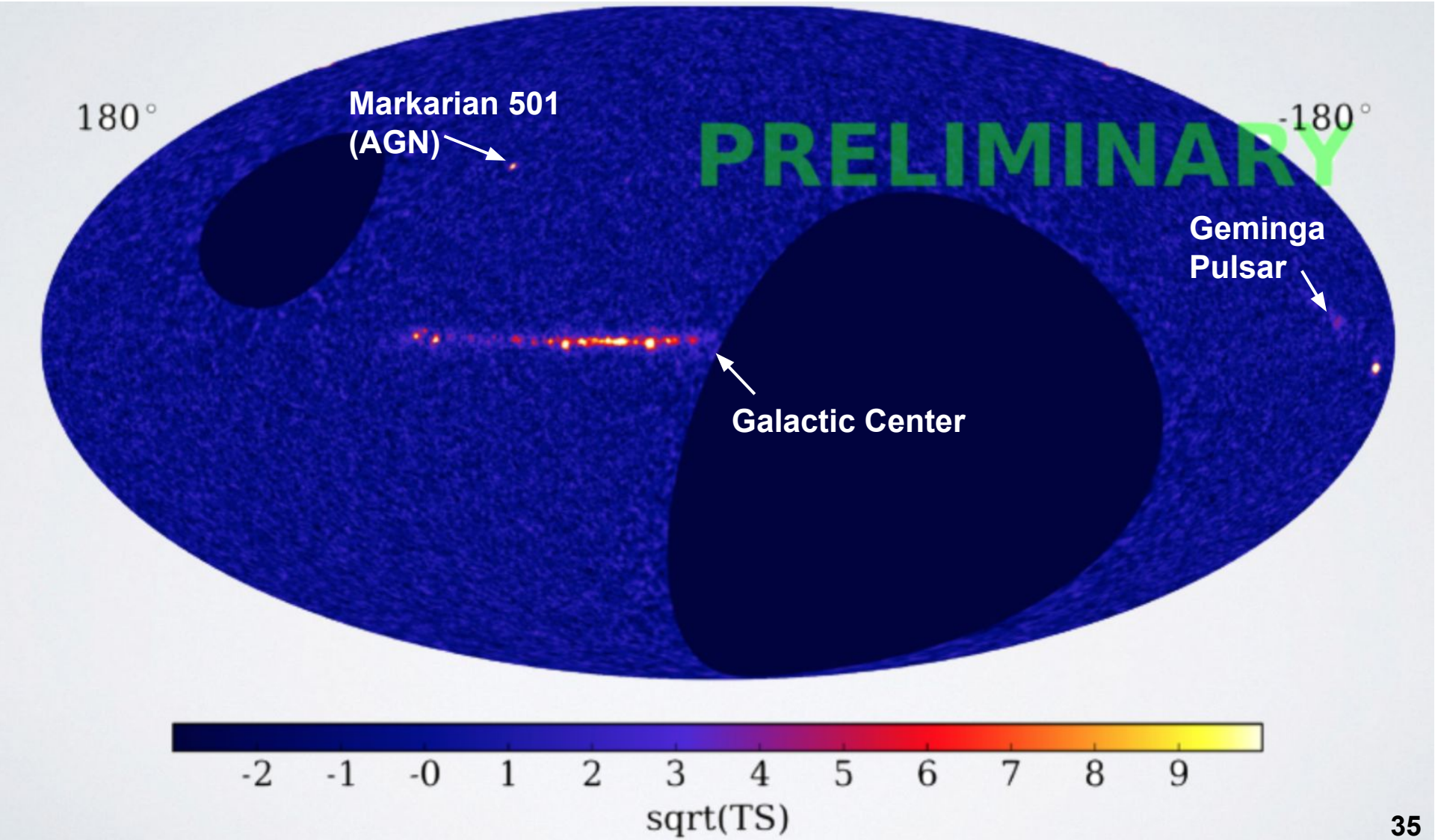


Fermi LAT GeV Gamma-ray Sky



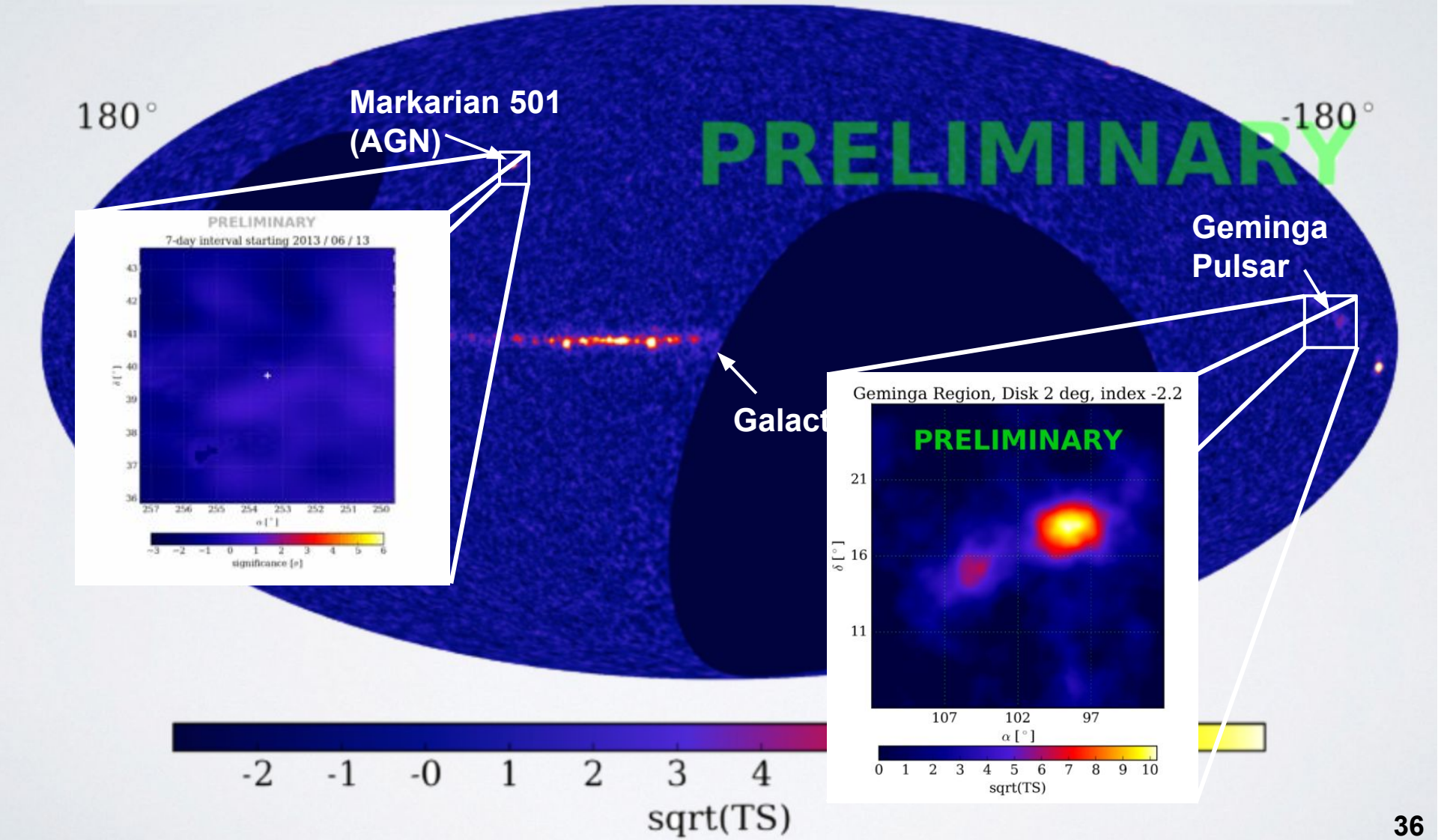
HAWC TeV Gamma-ray Sky

HAWC 1 year >1 TeV



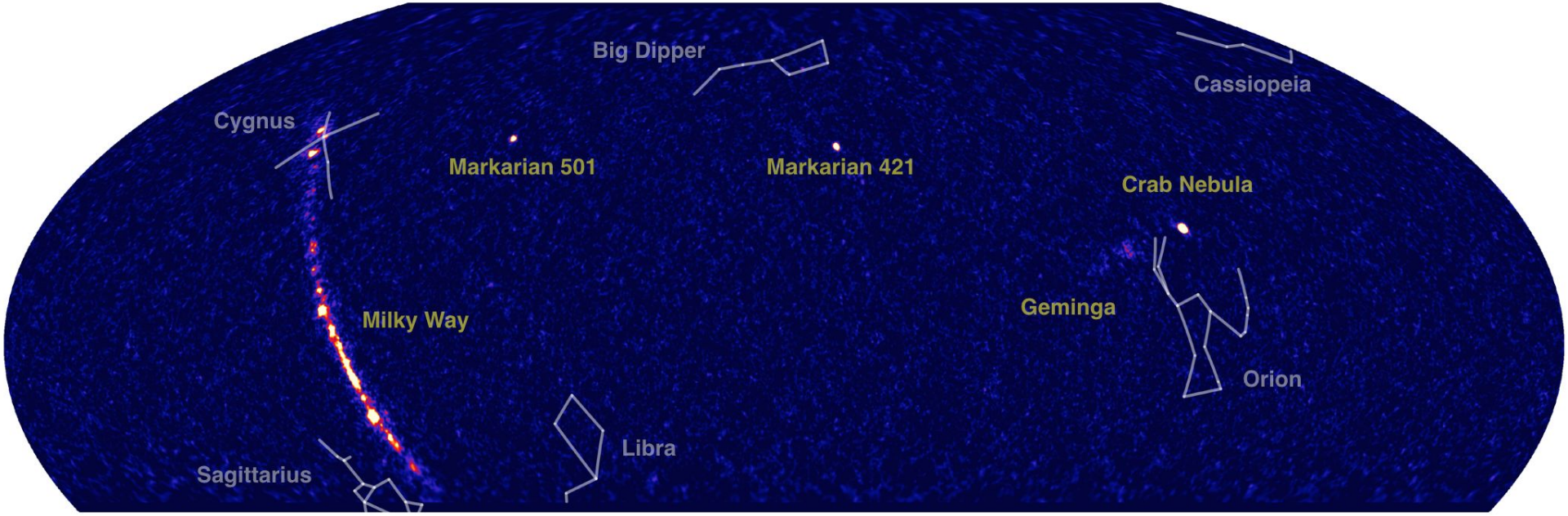
HAWC TeV Gamma-ray Sky

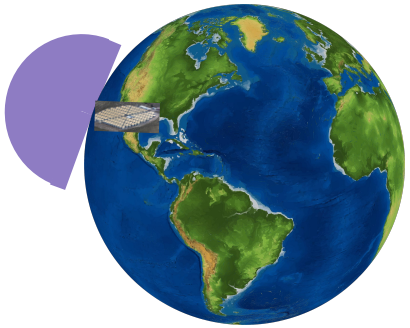
HAWC 1 year >1 TeV



HAWC TeV Gamma-ray Sky

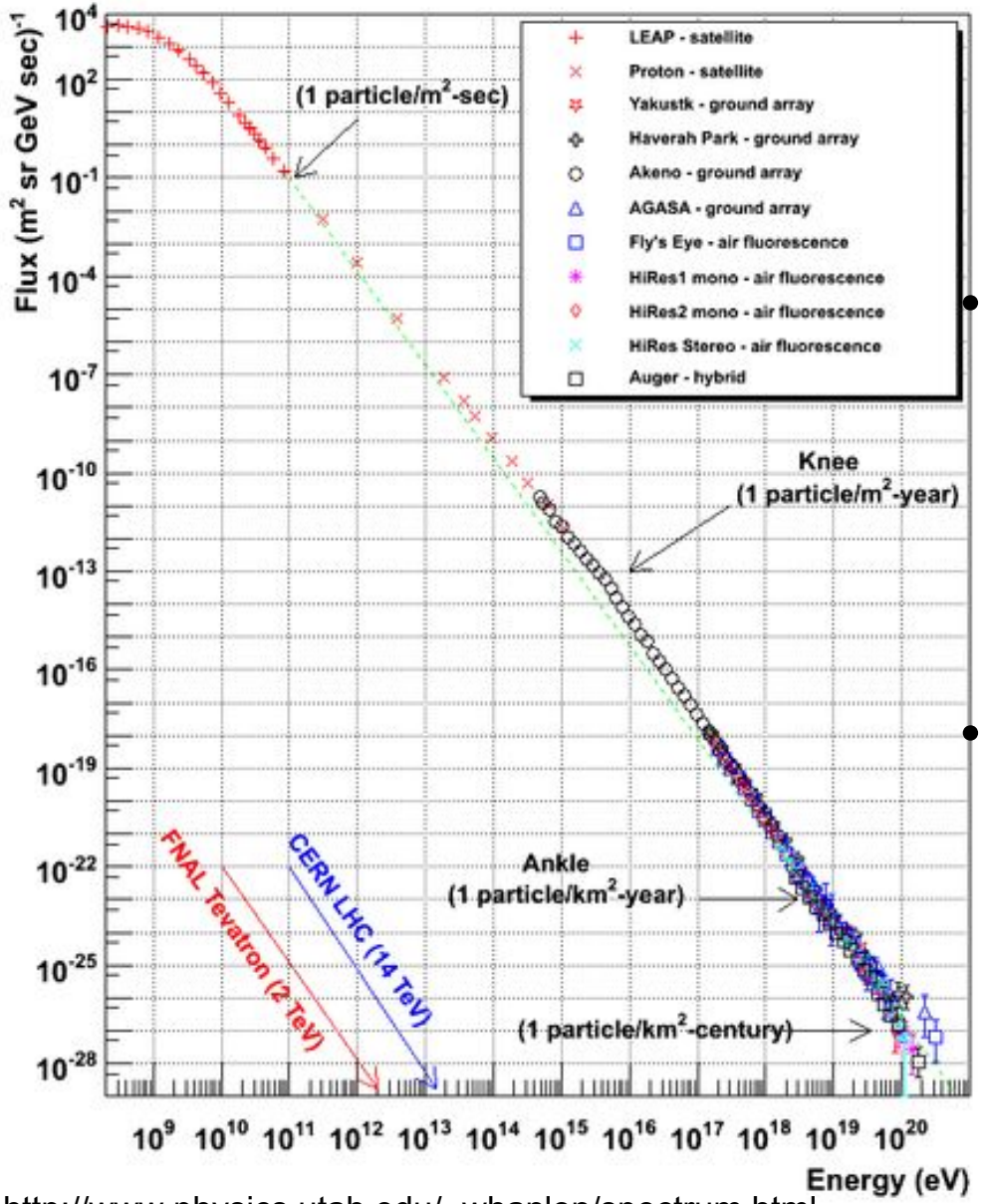
HAWC 1 year >1 TeV Equatorial Coordinates





At a latitude of ~20°, HAWC is can see the sky from about Declinations +60° to -20°

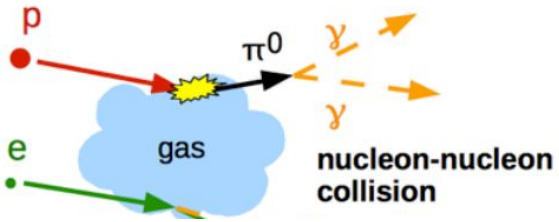
What is the source of high-energy cosmic rays?



- Here 'cosmic rays' = particles like protons and electrons
  - different than γ rays
- We observe particles with 10,000,000 times more energy than the collisions at the LHC
  - Where do these come from?
  - What is giving them all that energy?
- Highest energy events are rare and require huge arrays like Pierre Auger
  - Pierre Auger area is ~1,000 km^2
  - 'Oh my god' particle observed with $E = 3*10^{20}$ eV in 1991 with Fly's Eye (Utah)

http://www.physics.utah.edu/~whanlon/spectrum.html

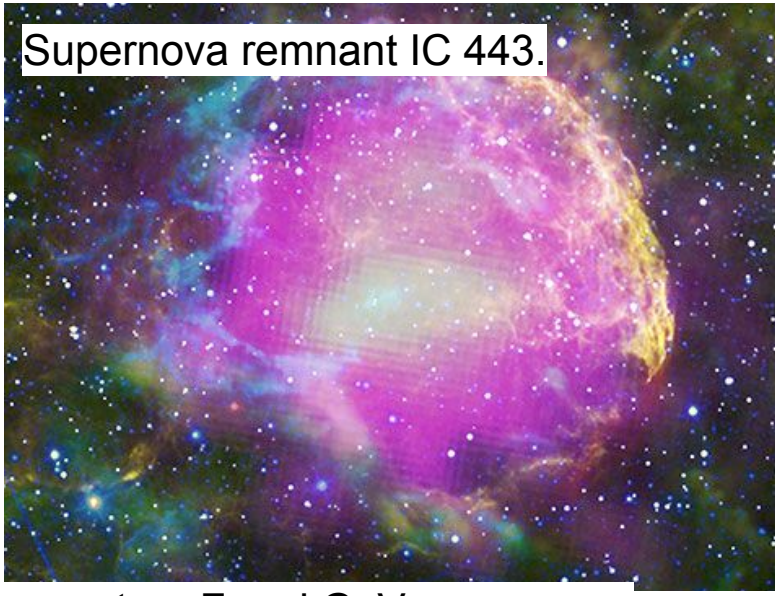
Cosmic-ray Protons should make pions



$$p+p \rightarrow p+p+\pi^0 \qquad \pi^0 \rightarrow \gamma\gamma$$

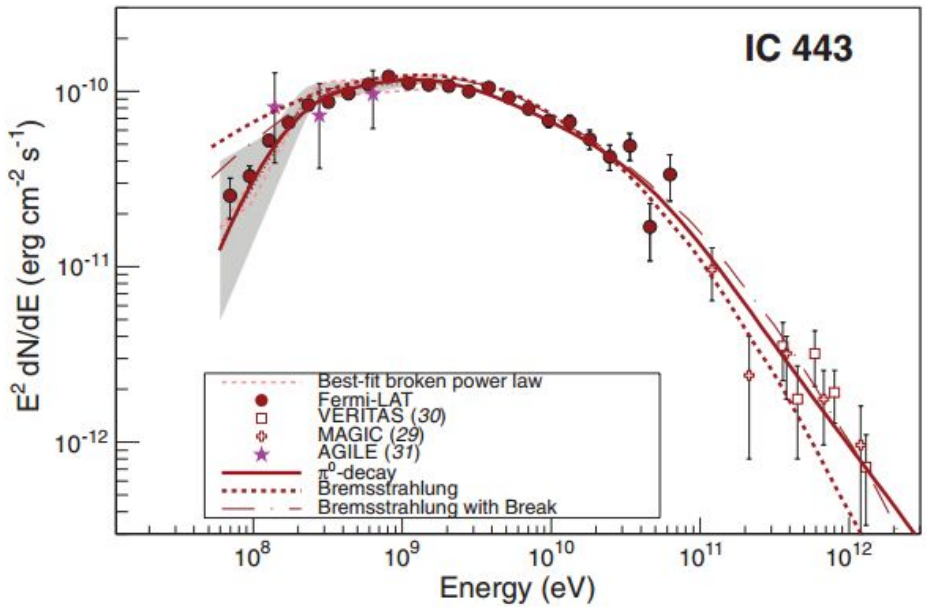
- **high-energy protons will create pions**
  - **neutral pions quickly decay to a pair of gamma rays**
  - **energy spectrum of gamma rays from pion decay would peak at $m_{\pi 0}/2 \sim 70$ MeV**

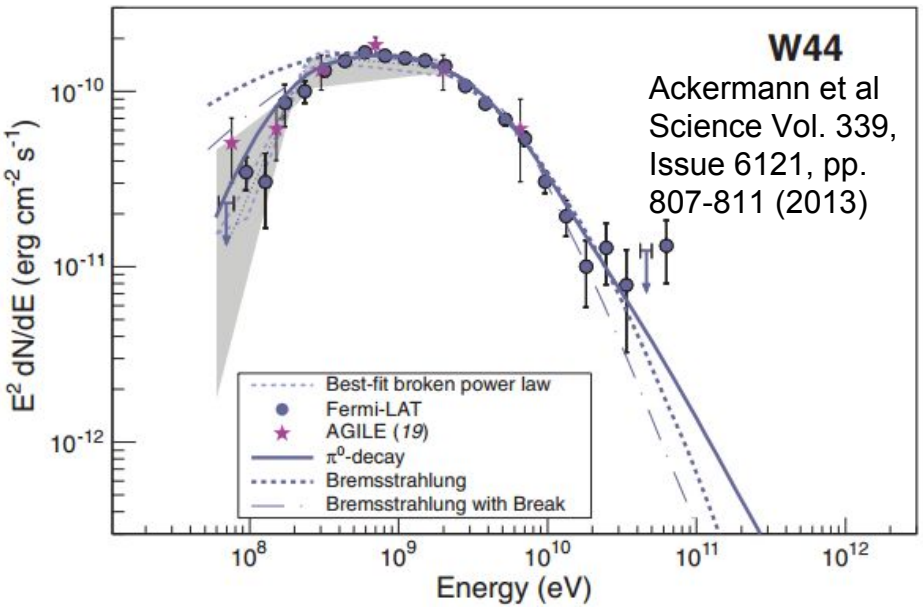
- **Supernova remnants are possible sources of cosmic-ray proton acceleration**
  - **to test this hypothesis, we can search for the 'pion bump' using the Fermi LAT**



magenta = Fermi GeV gamma-ray emission,
yellow = optical wavelengths,
blue, cyan, green, red = infrared data (3.4, 4.6, 12, 22 microns)
Credit: NASA/DOE/Fermi LAT Collaboration, NOAO/AURA/NSF, JPL-Caltech/UCLA
https://www.nasa.gov/mission_pages/GLAST/news/supernova-cosmic-rays.html

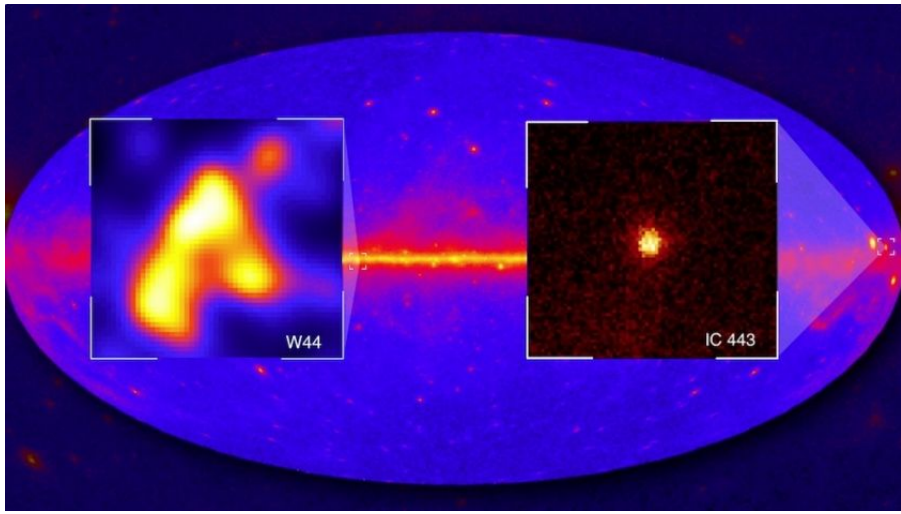
Pion Bump Seen in Supernova Remnants





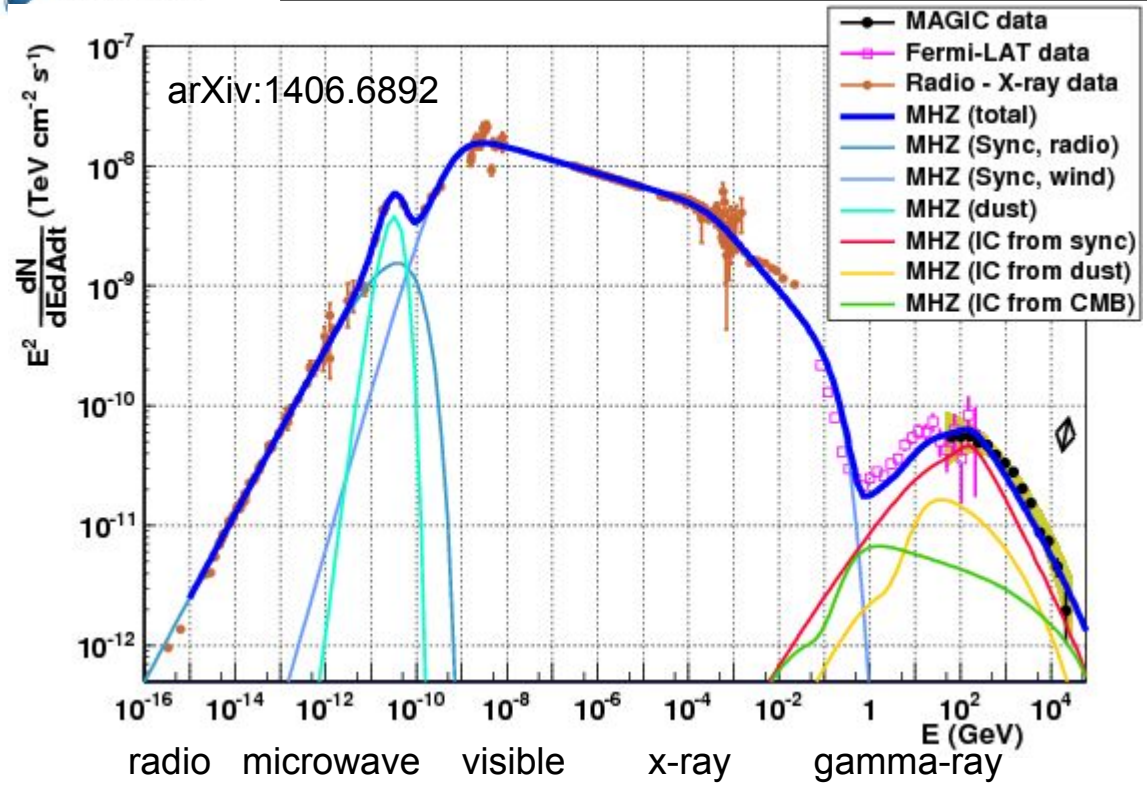
Ackermann et al Science Vol. 339, Issue 6121, pp. 807-811 (2013)

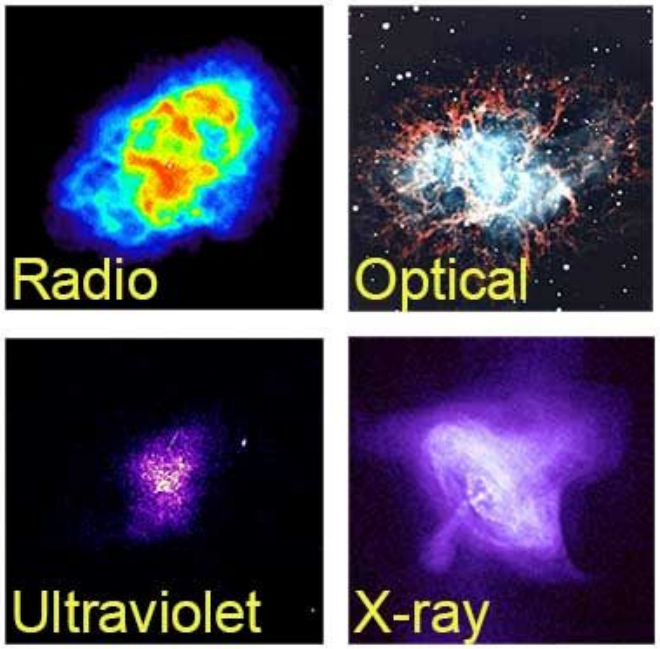
- **pion bump seen from two supernova remnants: IC 443, W44**
  - **direct detection that supernova remnants are cosmic-ray proton accelerators**
- **protons required to make these gamma rays only require energies up to ~1 TeV**
  - **doesn't explain 'oh my god' particle**



Fermi-LAT gamma-ray image of two supernova remnants: W44 and IC 443

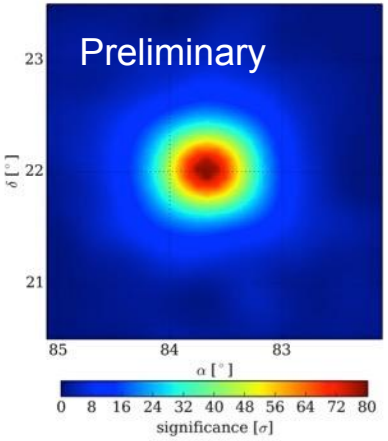
The Crab Nebula





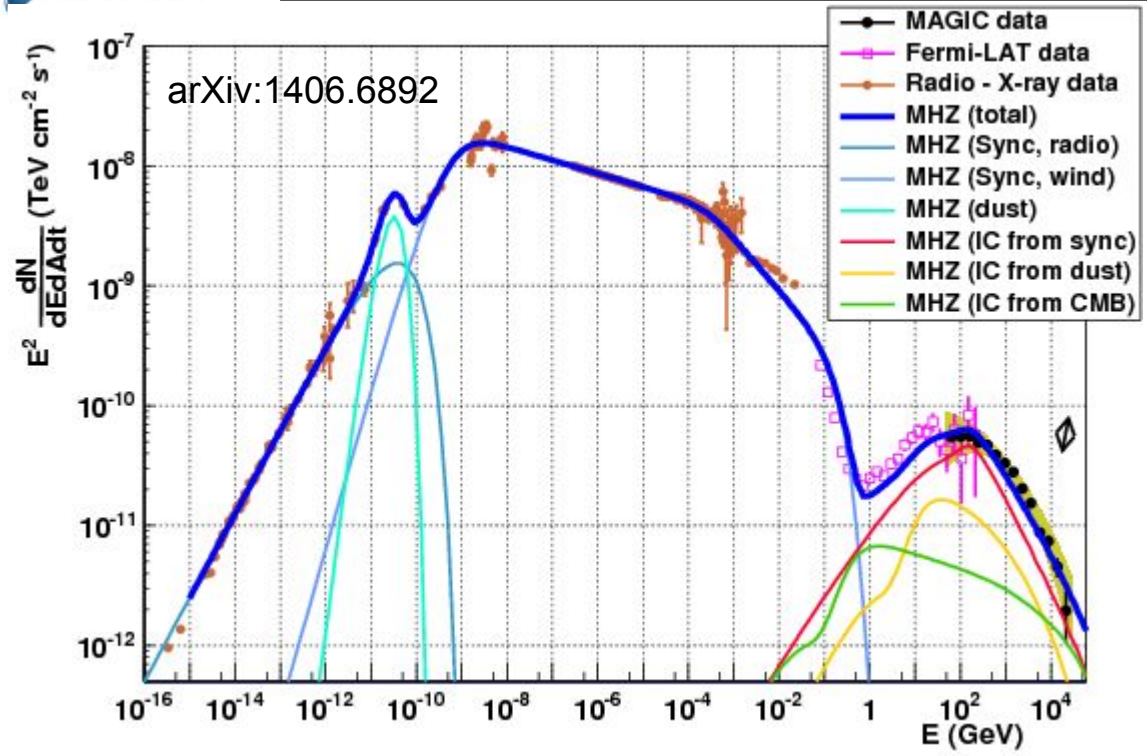
Crab Nebula in various wavelengths
credit: GFSC/NASA

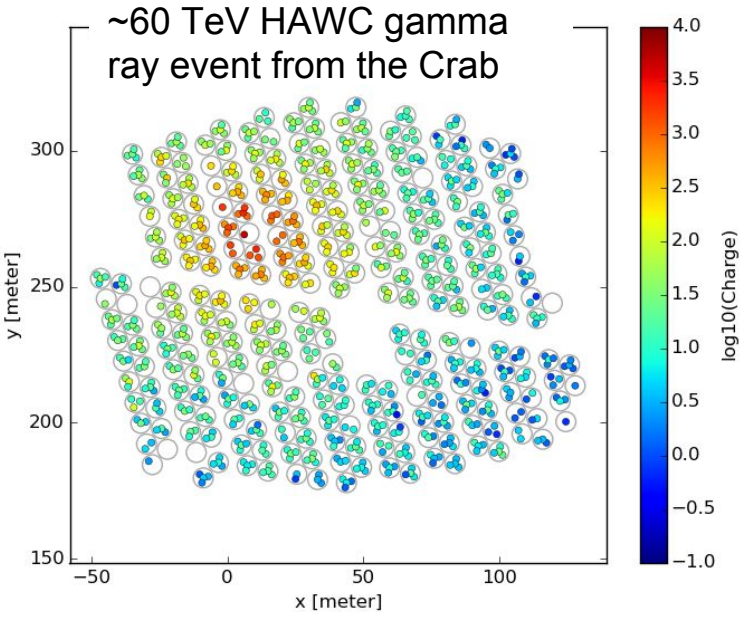
- **Space must also accelerate electrons**
  - **high energy electrons observed by e.g. AMS**
- **Know Pulsar Wind Nebula power electrons since we see synchrotron emission in radio/microwave**
  - **high energy electrons upscatter Cosmic Microwave Background (CMB) photons to gamma rays**
    - **inverse Compton (IC)**



HAWC 1 year Crab

The Crab Nebula -- Looking for the Highest Energy Gamma Ray



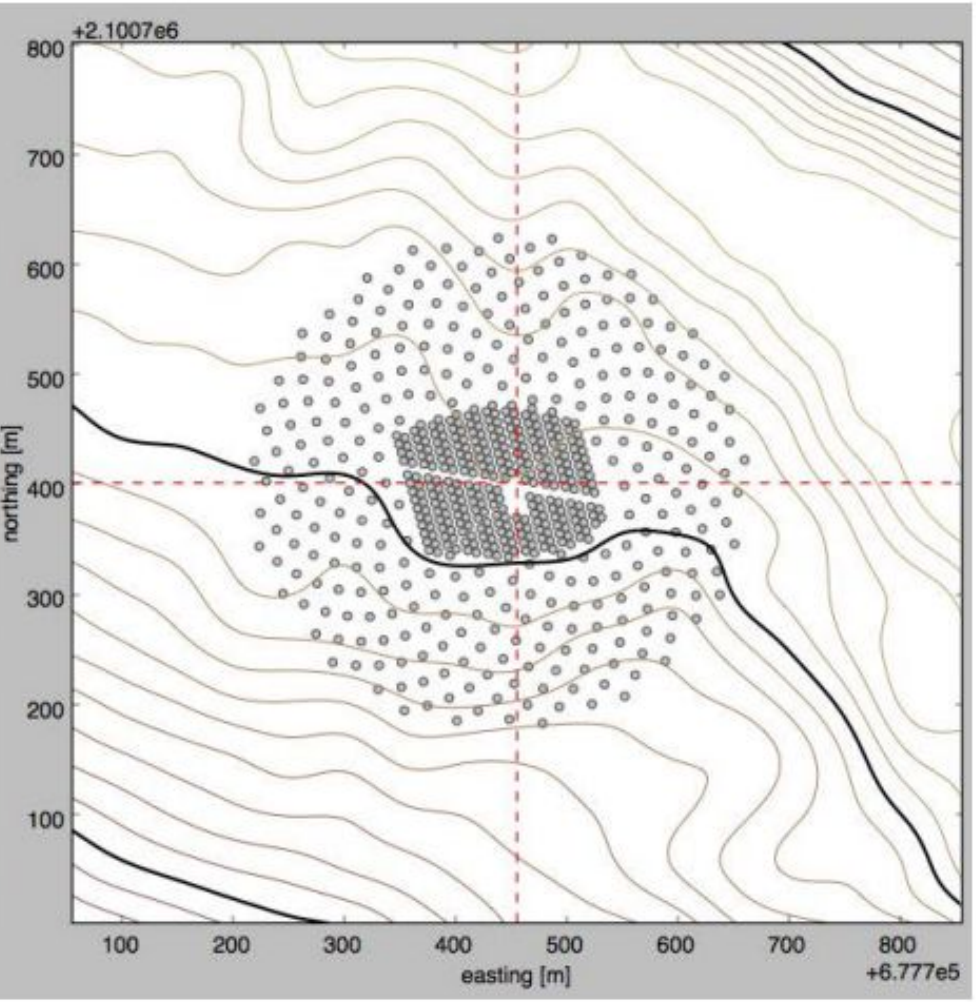


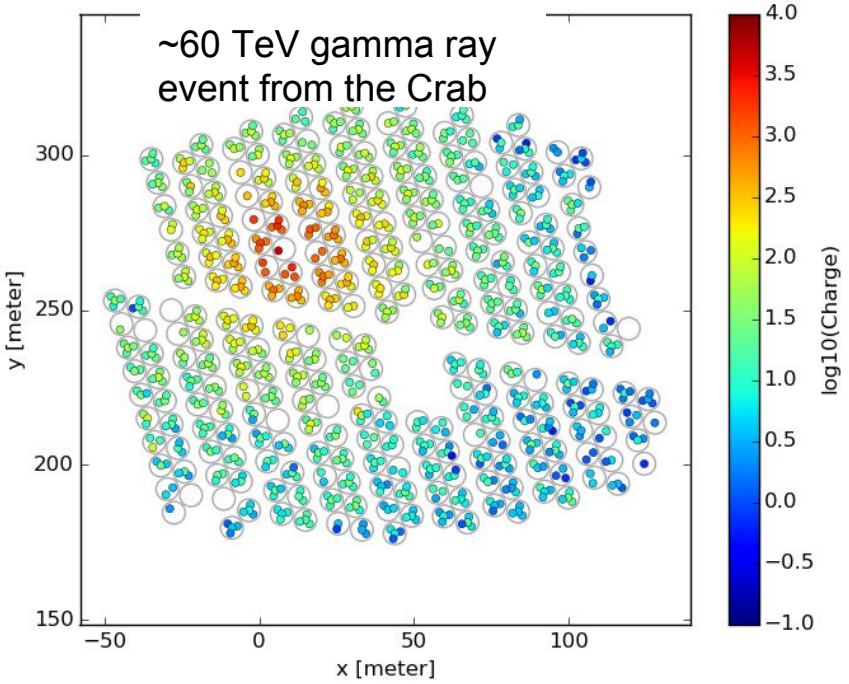
- **Inverse Compton component decreases rapidly at high energies**
  - **electrons lose energy too quickly to get energetic enough to create greater than about 60 TeV gamma rays**
  - **high energy protons are expected to create highest energy gamma rays**

- **HAWC is primed to observe the highest energy gamma ray ever detected**
  - **upgrade underway to expand array and improve sensitivity above 10 TeV by a factor of 3-4**

Upgrade to HAWC Array

A. Sandolval arXiv:1509.04269

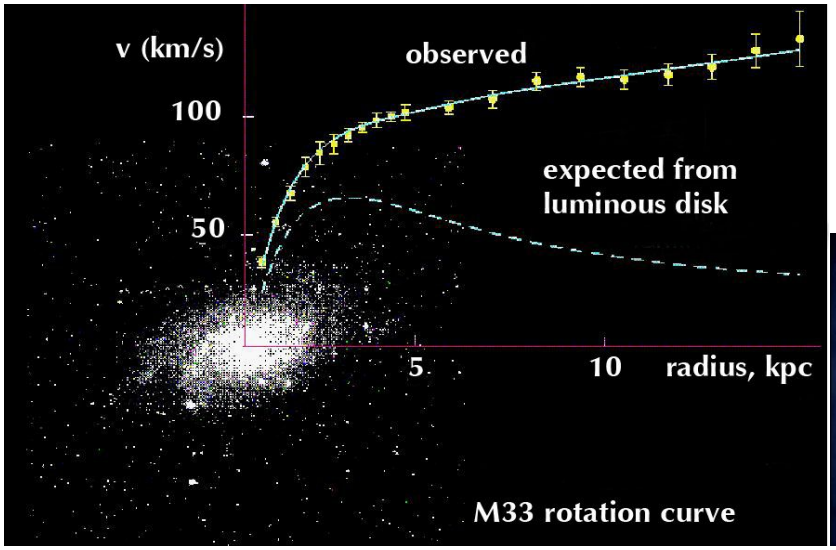


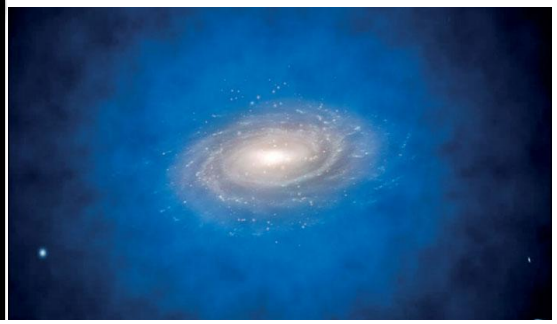


- **Upgrade to HAWC array is underway**
  - **add larger, sparse array of small tanks**
- **Provide better measure of high energy showers**
  - **expect gain in sensitivity > 10 TeV of about 3-4**

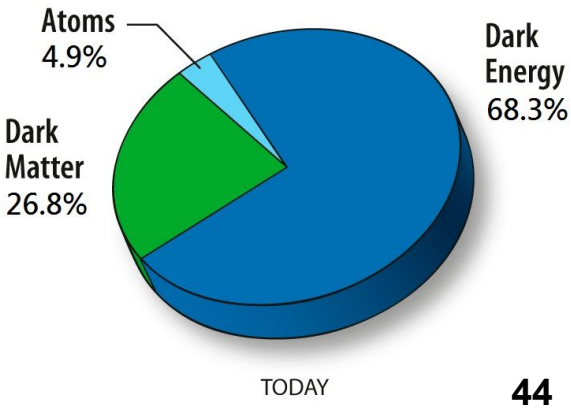
Searching for Dark Matter with Gamma Rays

- **Dark Matter is the gravitational glue that holds e.g. galaxies together**



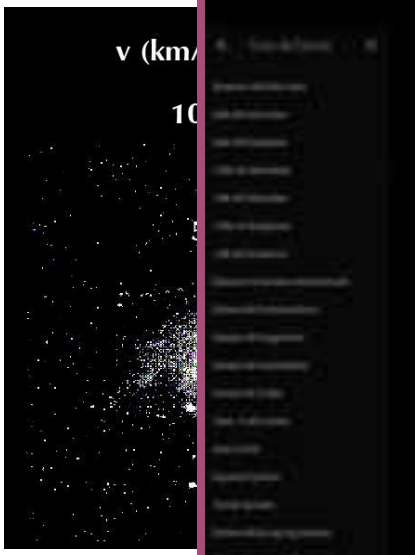


- **Weakly Interacting Massive Particle**
  - **promising DM candidate**
  - **fundamental particle beyond Standard Model**
    - **Being searched for at LHC and underground experiments (e.g. LUX)**
  - **WIMP annihilations may produce γ rays**
    - **weak scale annihilation cross section ➜ observed abundance of DM**



Searching for Dark Matter with Gamma Rays

- **Dark Matter is the gravitational glue that**



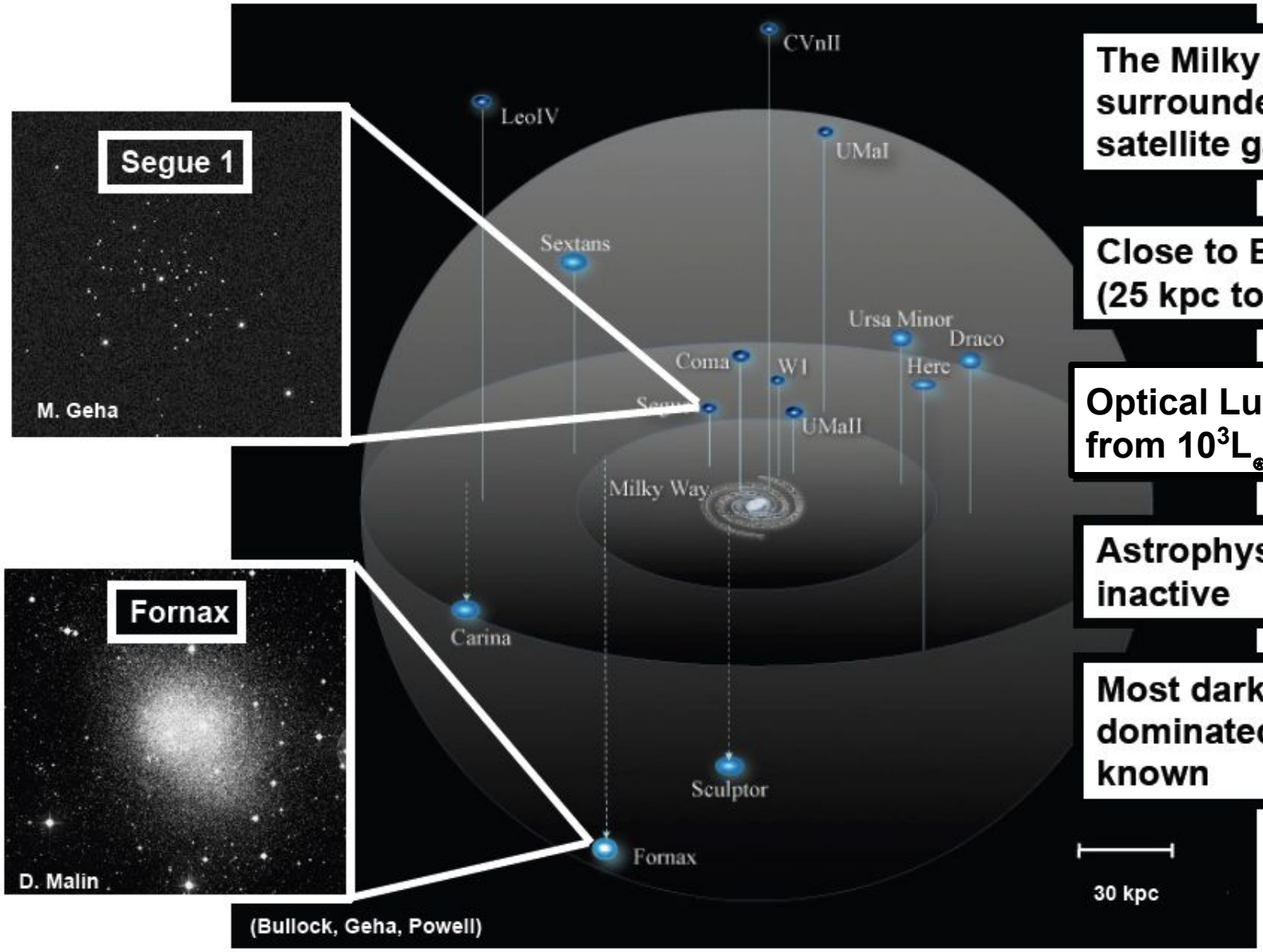
Gamma-rays

eutrinos

Dark Energy 68.3%

- **Weakly**
  - **pro**
  - **fun**
  - **WI**

Milky Way Dwarf Spheroidal Galaxies



The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

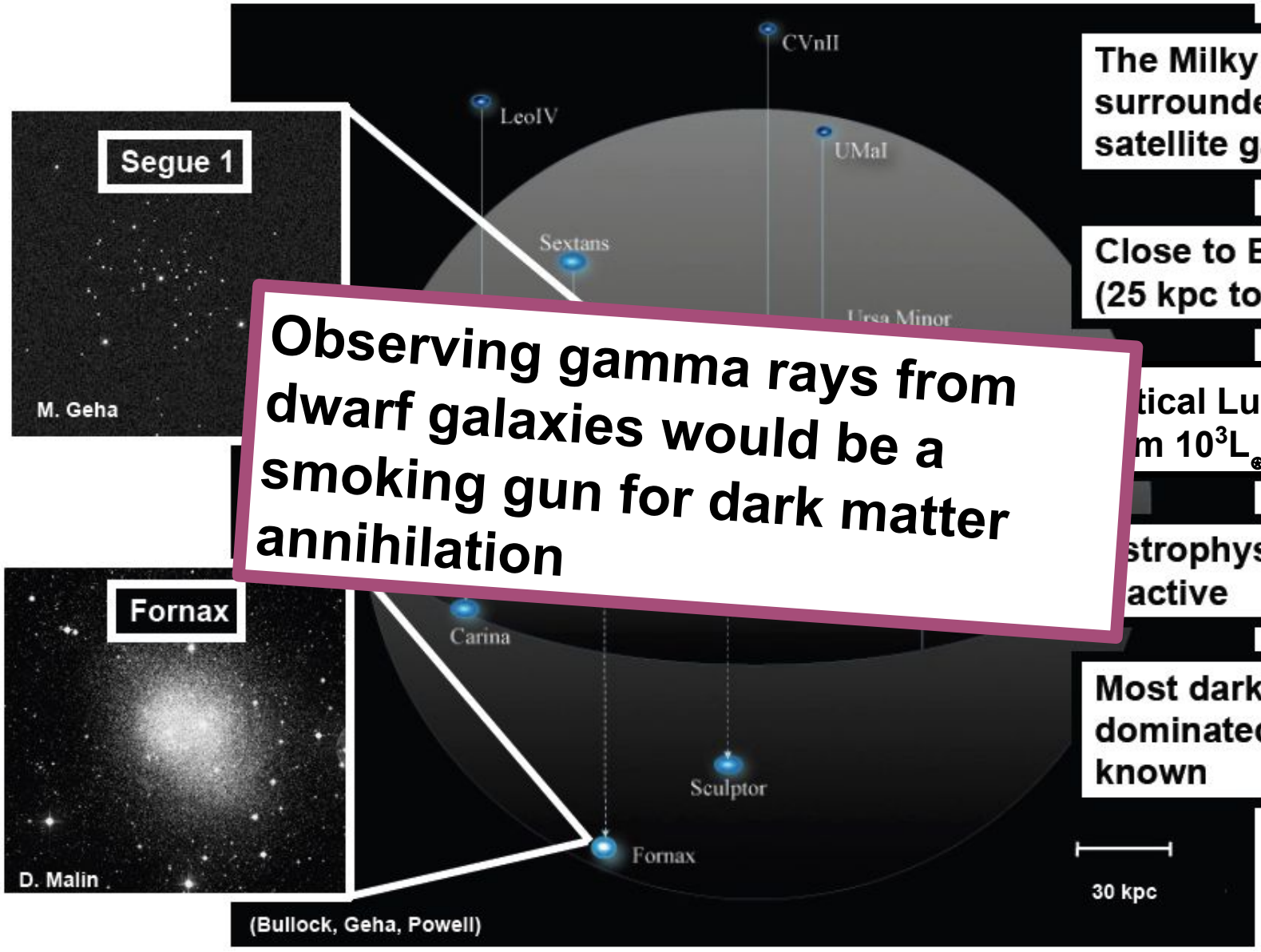
Optical Luminosities from $10^3 L_\odot$ to $10^7 L_\odot$

Astrophysically inactive

Most dark matter dominated objects known

Slide credit: A.Drlica-Wagner

Milky Way Dwarf Spheroidal Galaxies



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Close to Earth (25 kpc to 250 kpc)

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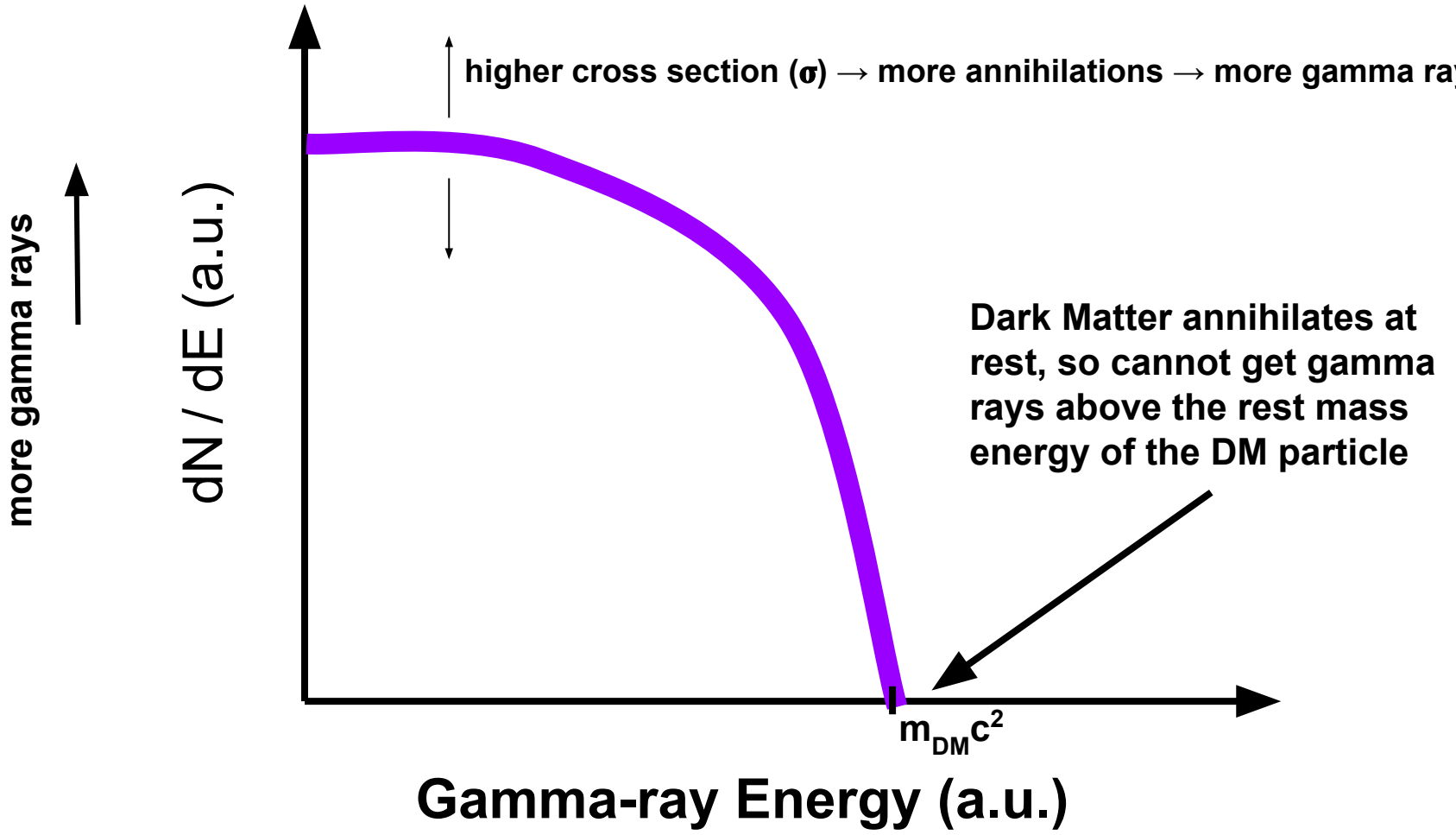
strophysically
active

Most dark matter dominated objects known

Observing gamma rays from dwarf galaxies would be a smoking gun for dark matter annihilation

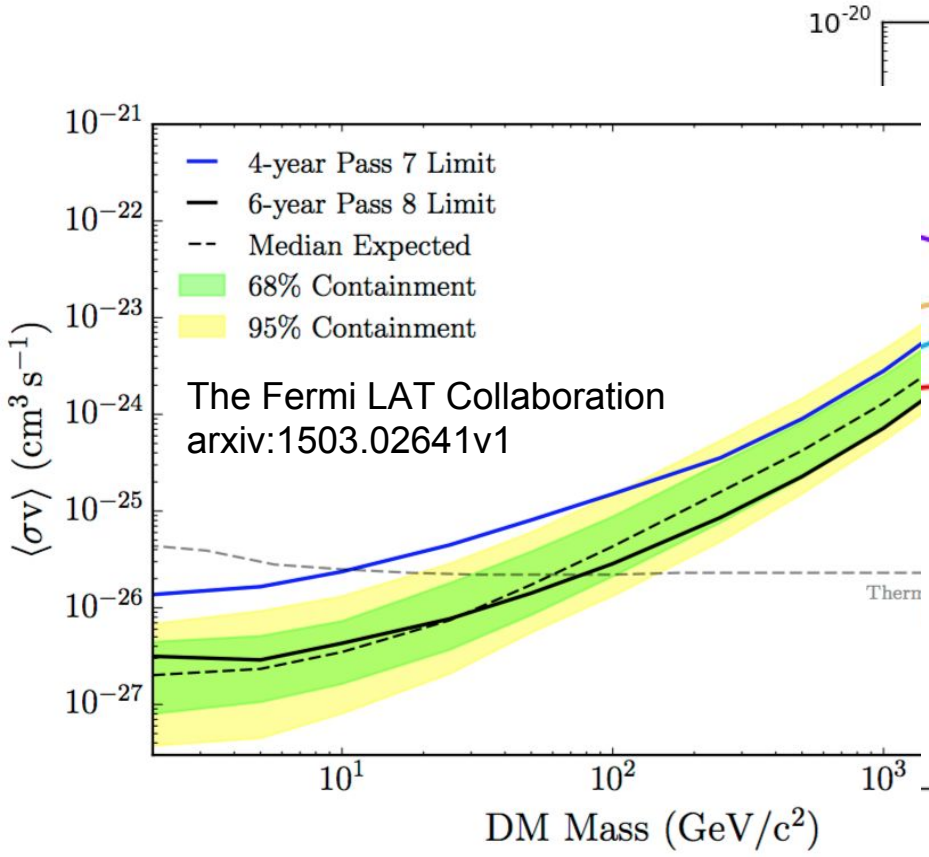
Slide credit: A.Drlica-Wagner

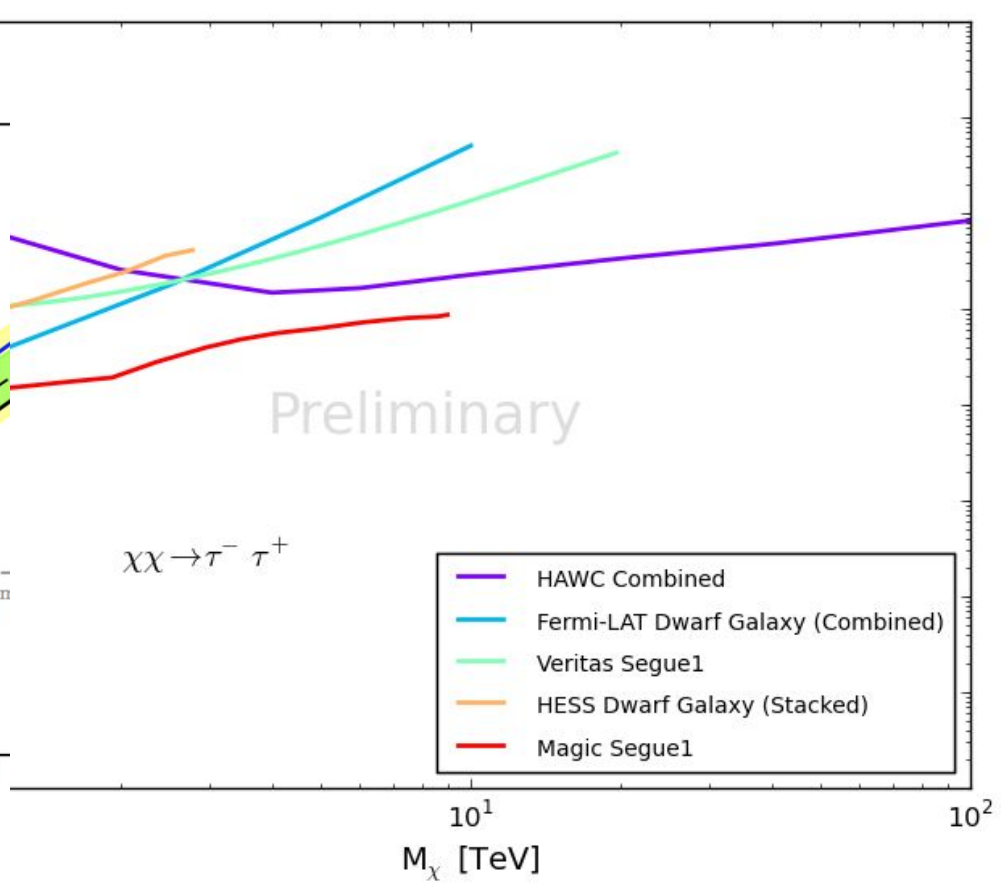
Gamma Rays from Dark Matter



σ is the annihilation cross section. Larger σ means there is a larger chance of interaction.

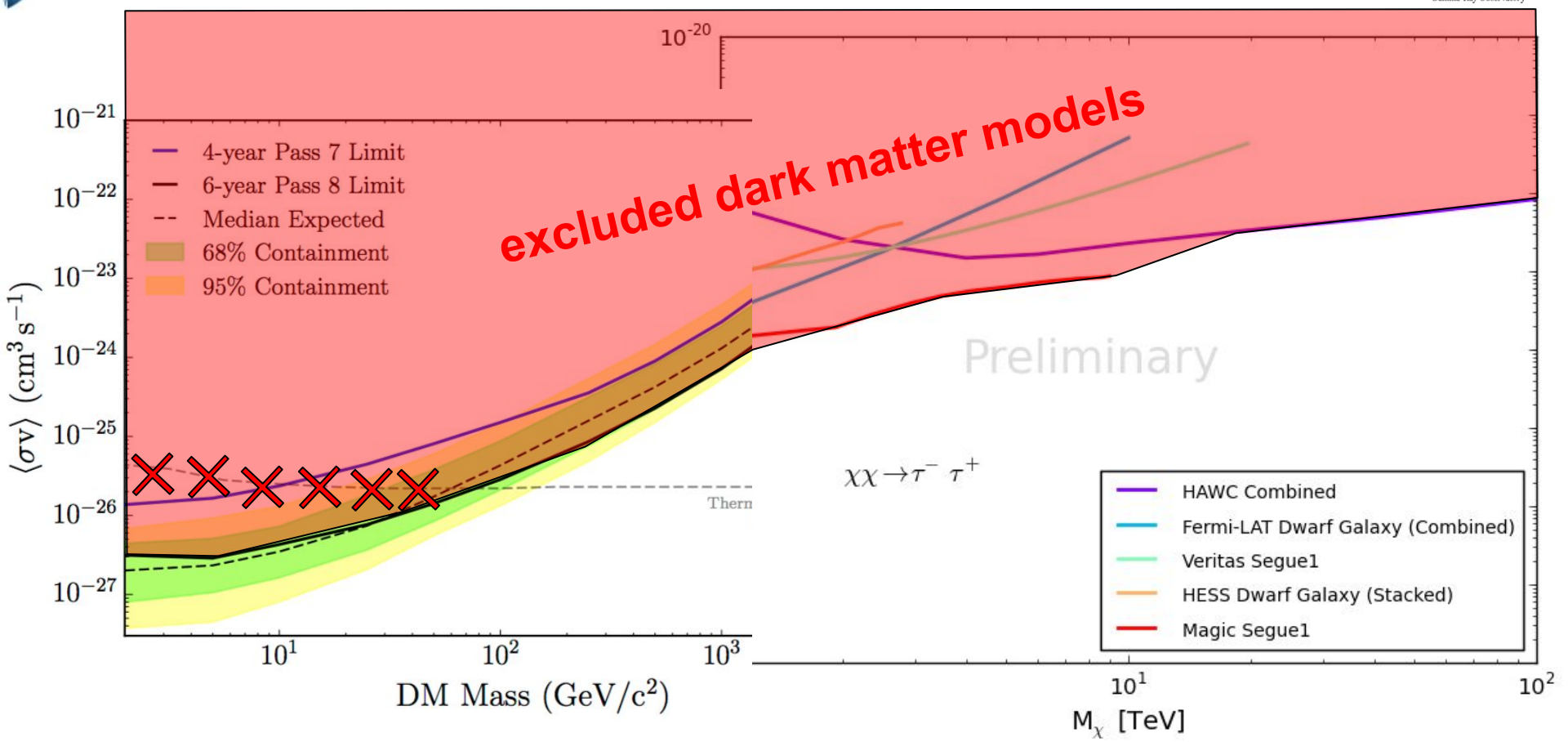
Limits from Dwarf Galaxies





- **No gamma-ray excess observed in dwarf galaxies**
- **Together Fermi LAT and HAWC limits constrain dark matter models for masses from ~2 GeV to 100 TeV**

Limits from Dwarf Galaxies



- **No gamma-ray excess observed in dwarf galaxies**
- **Together Fermi LAT and HAWC limits constrain dark matter models for masses from ~2 GeV to 100 TeV**

Summary

- **The Fermi LAT is an awesome particle detector in space!**
  - **in orbit for 8 years and counting**

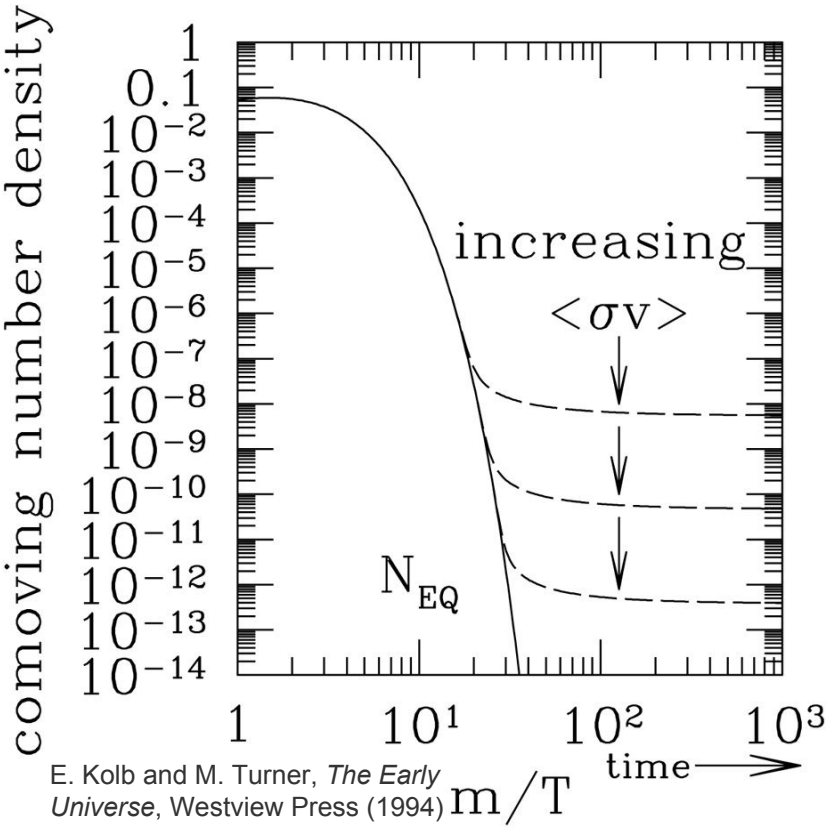
- **HAWC is an awesome particle detector in the highest mountains in Mexico!**
  - **Operating with full array since March 2015**
  - **New detector expansion underway to reach highest gamma ray energies**

- **Gamma rays tell us about high energy particle physical mechanisms in space**
  - **help us answer fundamental questions**
    - **"where/how are the high energy cosmic rays accelerated"**
    - **"what are the particle properties of dark matter"**

Backup

WIMPs

artist's concept



E. Kolb and M. Turner, *The Early Universe*, Westview Press (1994)

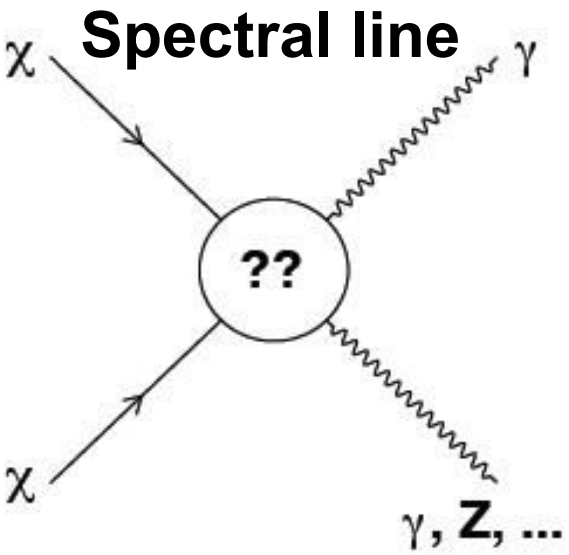
- **Weakly Interacting Massive Particle (WIMP, χ)**
  - **GeV - TeV mass scale**
  - **WIMPs may be thermal relics**
  - **e.g. neutralino (SUSY, electrically neutral, stable, motivated theoretically)**

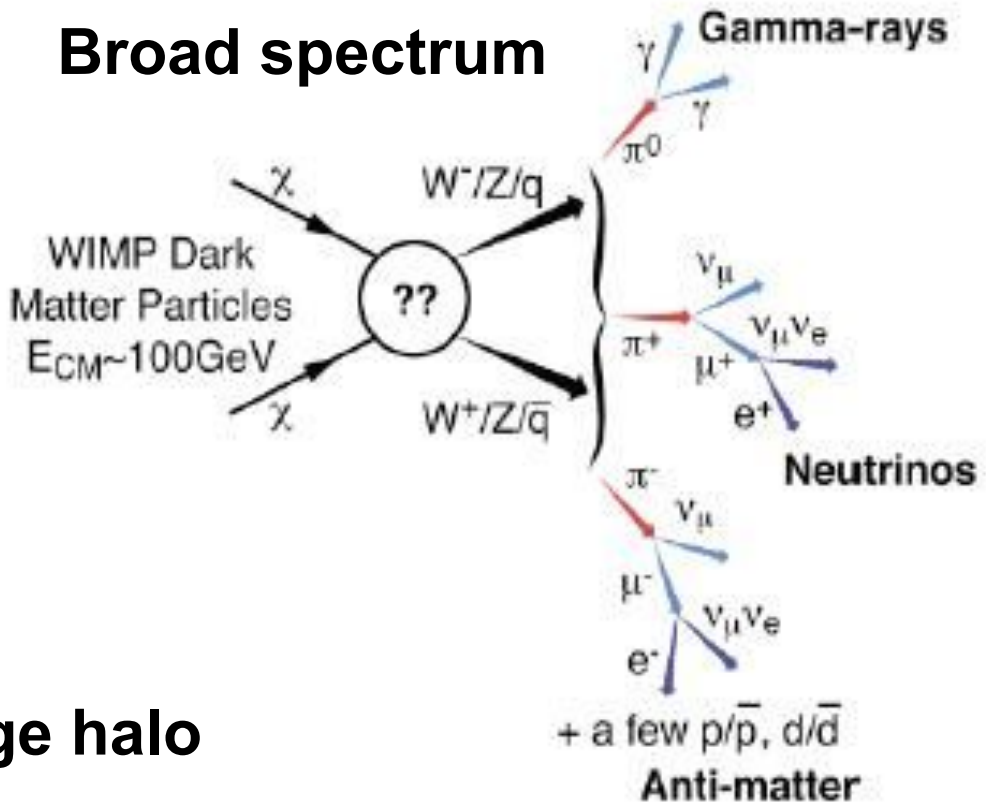
Assuming a weak scale σ_{ann} yields observed relic abundance

- **$\langle \sigma v \rangle_{ann} \sim 3 \times 10^{-26}$ cm^3/s ($\sigma_{ann} \sim 3$ pb at time of decoupling)**

Particle DM annihilation may produce Standard Model particles

Indirect Dark Matter Detection

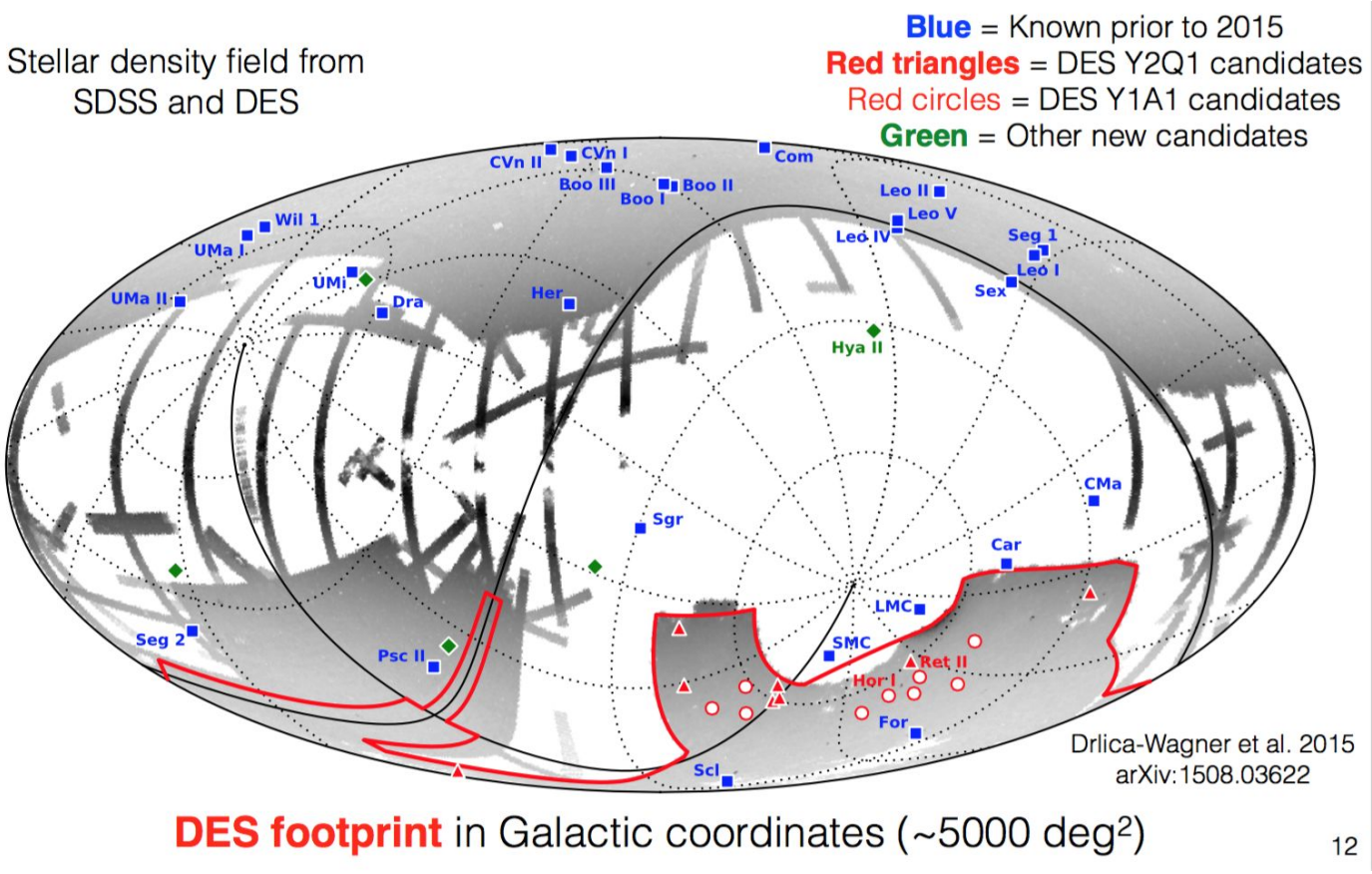




- The Milky Way sits in a large halo of cold DM ($v_{DM} << c$)
  - Expect additional DM overdensities (halos / subhalos)
    - e.g. Milky Way dwarf galaxies
    - e.g. Galaxy Clusters

WIMP annihilations (decays) may produce gamma rays

New Dwarf Galaxies Discovered!



- **Optical surveys are quickly improving in both sky-coverage and depth**
  - **~15 new dwarf galaxy candidates discovered with Dark Energy Survey (DES), Sloan Digital Sky Survey (SDSS), and Panoramic Survey Telescope and Rapid Response System (Pan-STARRS**
- **Fermi LAT and HAWC have already observed these objects due to all-sky coverage**